Effect of Ground Glass Composition on the Compressive Strength, Replacement Level, Hardened Air-Void System, and Microstructure of Portland Cement Mortars

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Dedication

This thesis and all the research accomplished to reach this point is dedicated to my family and friends who have supported me throughout this adventure. To my parents, Jeff and Michelle Moore, who have always pushed me out of my comfort zone, ensured I never lost my hunger to better myself, and made me into the man I am today. Without your never-ending love and support, I would never have made it this far in life. I will never sit out, I will always dance. I love you both!

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Abstract

Supplementary cementitious materials (SCMs) are often used to replace a portion of portland cement in concrete to enhance the properties or performance, improve the economy of the mixture, or to decrease the carbon footprint of the concrete. Currently, fly ash, slag, and silica fume are the most commonly used SCMs; this research considers ground glass as an SCM. For the past several decades, less than 30% of the glass in the municipal solid waste stream has been recycled. Utilizing ground glass as a pozzolan in concrete could provide a high-value market for this discarded glass, and help to reduce the amount of portland cement used, thereby reducing the CO_2 emissions associated with the concrete mixture. It is a common misconception that all waste glass is the same. Depending on where and how the glass is collected, a waste glass stream can consist of several different types of glass and contains various surface contaminants, which can affect its performance in concrete. 18 different waste glass sources from across the country were used to make mortars containing 20% and 30% portland cement replacement levels by mass. Compressive strength was measured at 1, 7, 28, 56 days, and 6 months to compare samples containing glass powder to a portland cement mixture and a Class F fly ash mixture. The hardened air void structure was analyzed past 6 months for five of the samples. Results indicated that variation in replacement level greatly affected compressive strength, while variation in composition slightly affected the compressive strength and the hardened air void structure. Results also indicated that something more, like contaminations, could have affected the final results for compressive strength and the

air-void structure. A microstructural investigation of the morphology of the glass mortars was also executed.

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1 Introduction and Scope

The first use of concrete can be dated back to ancient civilizations. Their knowledge and use of concrete led to construction wonders like the Colosseum and the Pantheon in Rome, the Parthenon in Greece, and possibly the Great Pyramids of Giza in Egypt. Today, concrete materials and methods have been drastically improved upon, giving way to amazing engineering and design capabilities.

Many countries have enacted environmental laws and regulations to decrease pollutants released into the air, land, and water. In concrete, the main ingredient is portland cement. The production of portland cement is responsible for significant carbon dioxide (CO_2) emissions. Islam et al. (2017) reports that the production of one ton of portland cement produces and releases around 0.9 tons of CO_2 as well as NO_x, SO_x, and other particulates into the atmosphere. In 2015, it was reported that portland cement clinker production contributed approximately 4% of total global anthropogenic emissions (Olivier et al., 2016). This makes portland cement production one of the highest emitting production processes out there. Due to the environmental concern over portland cement production, alternative materials, known as supplementary cementitious materials (SCMs), are often used to partially replace some of the portland cement in concrete, thereby lowering the carbon footprint.

SCMs can be divided into two main categories based on their chemistry: hydraulic or pozzolanic. Hydraulic materials, like portland cement, have a high calcia (CaO) and moderate silica (SiO_2) content in their composition. When these materials are combined

with water, hydration reactions occur forming calcium silicate phases. Pozzolanic materials, such as glass, have a low CaO content, but considerable amounts of silica (SiO_2) or alumina (Al_2O_3). Pozzolanic materials require the presence of calcium hydroxide ($Ca(OH)_2$) to form cementitious phases.

Today, over 80% of all ready mixed concrete contains on average 18% SCM replacement (Obla et al., 2012). The addition of a SCM, or pozzolan, to a mixture can improve the mechanical and durability properties of the concrete, in some cases reduce the cost of the mixture, and reduce the carbon footprint of the concrete. Fly ash, slag, and silica fume are the most prevalently used SCMs. Relatively new to the SCM market is ground glass. Strict compositional and contaminant requirements limit the amount of waste glass that can be melted down and reused to make new glass, so a great deal of waste glass gets put into landfills every year. This means there is a large amount of waste glass available for use in concrete.

Glass producers can make a variety of different types of glass to suit the needs of a specific application. Compositionally, all glass contains high amorphous silica content and typically a low to moderate calcia content, making it a suitable candidate for use as a pozzolan. When glass is ground to a fine powder, less than 45μm is ideal, and mixed with portland cement, it has been found to produce a concrete mixture that is strong and durable. Soda-lime glass is the most common glass utilized, but other glasses with varying chemical compositions also exist, and many times these different types become mixed within the municipal solid waste stream.

Glass composition varies from waste stream to waste stream. Therefore, it is necessary to understand the effects of a variable composition for glass to be successfully used as a pozzolan in portland cement concrete. As an example, fly ash is currently separated into Class C or F, based on its chemistry and corresponding performance. The goal here is similar. Determine if glass should also be treated differently based on composition, collection, and processing conditions.

When using glass powder as a pozzolan, there is a potential concern that its fresh and hardened properties can be affected due to soap or other contaminants. Glass is the only pozzolan with soap being an issue due to contaminants getting onto the glass while it is mixed with other recyclables and trash. The effect of contaminants like soap have not been investigated in the literature yet, but it is important to consider since it can affect properties like the water demand, permeability, and the hardened air void structure. The hardened air void structure provides a prediction of how well the mixture will do in freeze thaw conditions, which is extremely prevalent in cold areas. The size, shape, and number of air voids can determine if the mixture will do well or not in these cold areas. When contaminants like soap become part of the mixture, a film can be put over entrained air voids causing them to not be able to do their job or more entrapped air voids can form due to soapy bubbles forming and disappearing.

This research aimed to investigate how various glass compositions affect the compressive strength and hardened air void structure of portland cement mortars made with ground glass as a pozzolan. Eighteen waste glasses were collected from across the United States,

analyzed for composition, and ground down to have a D90 passing 45 micrometers (microns or μm). A modified strength activity index (SAI), based on ASTM C311 (2016), was used to determine the effect of the glass composition and replacement level on compressive strength. The modified version followed the test method found in ASTM C311 (2016) with the only difference being the addition of more testing days and replacement levels. The results of the modified method were used to investigate the compressive strength development of a variety of ground waste glass mixtures compared to a portland cement control mixture and a Class F fly ash pozzolan mixture.

The hardened air void structure was analyzed according to provisions provided in ASTM C457 (2016). Analyzing the hardened air void system can indicate a material's resistance to freezing and thawing cycles. Too large and too many air voids can make the concrete weak, whereas too little and not enough air voids can make the concrete less durable. These two tests are an effective way to determine the properties of the concrete with glass powder as a pozzolan. This research considered waste glass as an SCM and determined the effects of replacement level and composition on compressive strength and hardened air void properties.

1.1 Project Goals

The primary goal of this research was to investigate the effects of ground glass composition and replacement level on the compressive strength, hardened air void system, and microstructure of portland cement-based mortars. The three primary questions addressed in this research are:

1. How does the glass composition and replacement level affect the early and later age compressive strength of portland cement-based mortars when used as a pozzolan?
2. How do glass composition and processing parameters affect the hardened air-void structure of portland cement-based mortars when used as a pozzolan?
3. How do glass composition and processing parameters affect the microstructure in portland cement-based mortars when used as a pozzolan?

To answer these questions, samples of recycled glass streams from various processors around the United States were collected, labeled, and stored carefully to prevent cross contamination. All glass samples were ground below 45μm and analyzed for chemical composition using X-ray fluorescence (XRF). The work was split into two phases:

Phase I – In order to investigate the effect of composition and replacement level on compressive strength of different sample types, one portland cement control mixture was made, two mortar mixtures were made with a 20 and 30% replacement of Class F fly ash by mass, and twenty-eight mortar mixtures were made with 20 and 30% replacement of fourteen different glasses by mass. To determine compressive strength, 2”x2”x2” mortar cubes were cured in a humidity chamber and compressive strength was measured on three cubes per mixture at 1, 7, 28, 56, 90, and 182.5 days.

Phase II – In order to investigate the effects of composition, replacement level, glass collection methods, and subsequent surface contamination on the compressive strength,

hardened air-void structure, and microstructure of glass samples, four additional glasses were investigated. The glasses added in Phase II included one that came directly from a material recycling facility (MRF) and is considered dirty, one from an MRF that underwent a cleaning treatment, plate glass, and a bottle drop off glass. These glasses were selected to investigate the effects of surface contaminants from materials, such as soap, that could have been in the glass powder during collection. A total of eight mixtures were made with 20 and 30% replacement by mass and compressive strength was measured on three cubes per mixture at 1, 7, 28, 56, 90, and 182.5 days. A total of fifteen 2”x2”x2” mortar cube mixtures, including portland cement and Class F fly ash samples, at 20% replacement were used for hardened air-void and microstructural characterization. Hardened air-void analysis and microscopy was performed on three mortar cube samples per mixture at various curing ages. Microstructural characterization of the samples was performed using a scanning electron microscope (SEM) to perform secondary electron imaging (SEI), backscattered electron imaging (BSE), and energy-dispersive spectroscopy (EDS).

1.2 Thesis Organization

This thesis includes four additional chapters. Chapter 2 consists of a review of the literature and includes information on pozzolans, the pozzolanic reaction, and previous research performed on glass as a pozzolan in portland cement concrete. Chapter 3 discusses the test methods and materials used throughout the project. Chapter 4 presents the results from the tests discussed in Chapter 3 along with a discussion. Chapter 5 provides the conclusions made from this research and recommendations for future

research on this topic. There is also an Appendix A after Chapter 5 that shows more detailed results discussed in Chapter 4, Section 4.3.6.

2 Literature Review

2.1 Portland Cement Concrete

2.1.1 History of Concrete

Concrete is one of the most commonly used materials in the world. Concrete is used to build roads, sidewalks, buildings, and even artwork. Current concrete production methods are different than when it was first introduced to the world. The oldest concrete recorded was found in Galilee, Israel and dates to 7000 BC (Kosmatka and Wilson, 2016). It was called lime concrete and was made from burning limestone to produce quicklime. Since 7000 BC, changes were made to the concrete production process with the next oldest concrete dating back to 5000 BC. This concrete consisted of the first known pozzolan used, diatomaceous earth. The Greeks in 500 BC, followed by the Romans in 300 BC, expanded on the use of natural materials and produced their concrete by using the excessive amount of volcanic ash they gathered from Mount Vesuvius. By utilizing natural materials in the production of concrete innovative ways were sparked to make concrete more efficient and effective. Today, concrete can consist of a variety of materials ranging from straight portland cement to natural or recycled materials used as SCMs. Regardless of how far humans have improved concrete, there will always be a way to make concrete better.

The cement used most prevalently today is called portland cement. Portland cement was invented by Joseph Aspdin in England in 1824. Portland cement received its name due to the product resembling the color of the natural limestone quarried on the Isle of Portland

in the English Channel. In 1845, I.C. Johnson of White and Sons in Swanscombe, England expanded on Aspdin's cement by burning the raw materials with strong heat until it was converted into a glasslike substance (Kosmatka and Wilson, 2016). This manufacturing process served as the basis for the processes that are used today.

2.1.2 Portland Cement

As shown in Figure 2.1, portland cement production has steadily increased over the past 85 years, and projections indicate that this trend will continue into the future. As there are significant carbon emissions associated with portland cement production, global anthropogenic CO_2 also continues to be on the rise with portland cement clinker production contributing to about 4%. The negative environmental consequences of portland cement production acts as a strong driver for research and development of portland cement replacements and even alternative binders.

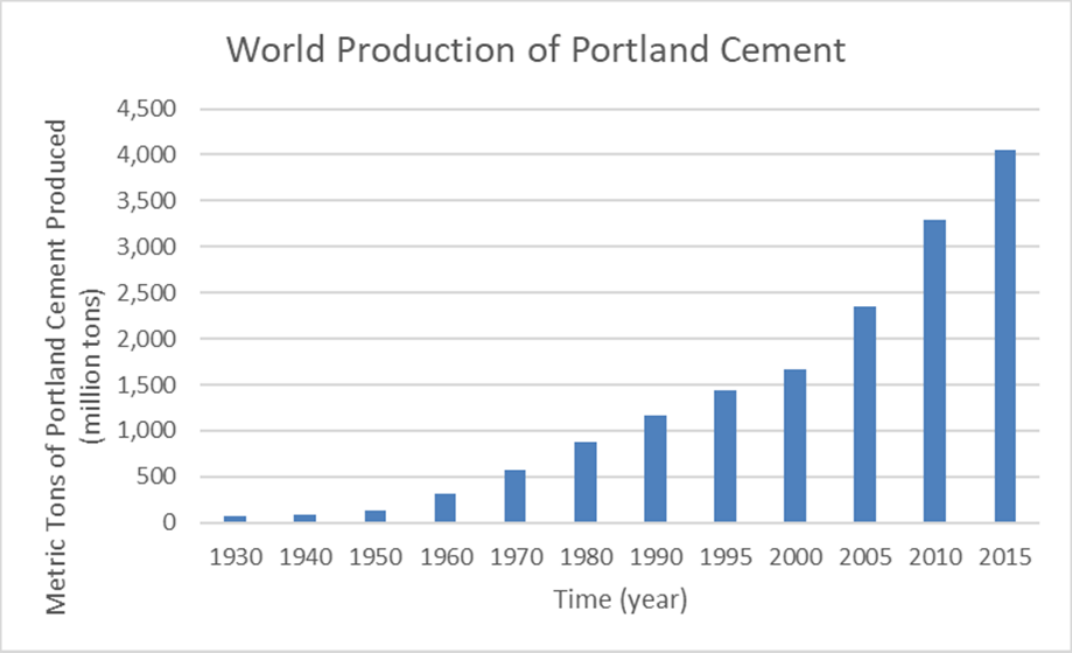


Figure 2.1.Total world cement produced from 1930 to 2015 (USGS, 2017).

Kosmatka and Wilson (2016) provide information on the portland cement production to help further understand the chemistry of portland cement and the causes of the high emissions associated with it. Table 2.1 will help clarify some cement chemist notation that is shown in this paper.

Table 2.1. Cement chemist notation for common compositions found in pozzolans.

Chemical Composition	Abbreviation	Name
SiO_2	S	Silicon Dioxide or Silica
Al_2O_3	A	Aluminum Oxide or Alumina
Fe_2O_3	F	Iron (II) Oxide
CaO	C	Calcium Oxide or Lime
H_2O	H	Water
$3CaO*SiO_2$	C_3S	Alite
$2CaO*SiO_2$	C_2S	Belite
$3CaO*Al_2O_3$	C_3A	Aluminate
$4CaO*Al_2O_3*FeO_3$	C_4AF	Ferrite
$CaO*H_2O$	CH	Calcium Hydroxide
$CaO*SiO_2*H_2O$	C-S-H	Calcium Silicate Hydrate
$CaO*Al_2O_3*SiO_2*H_2O$	C-A-S-H	Calcium Aluminate Silicate Hydrate

In the production of portland cement, first raw materials consisting of limestone, rock, and shale, clay, sand, or iron ore are mined, crushed and stored separately before being conveyed to the grinding mills. This is shown in Figure 2.2.

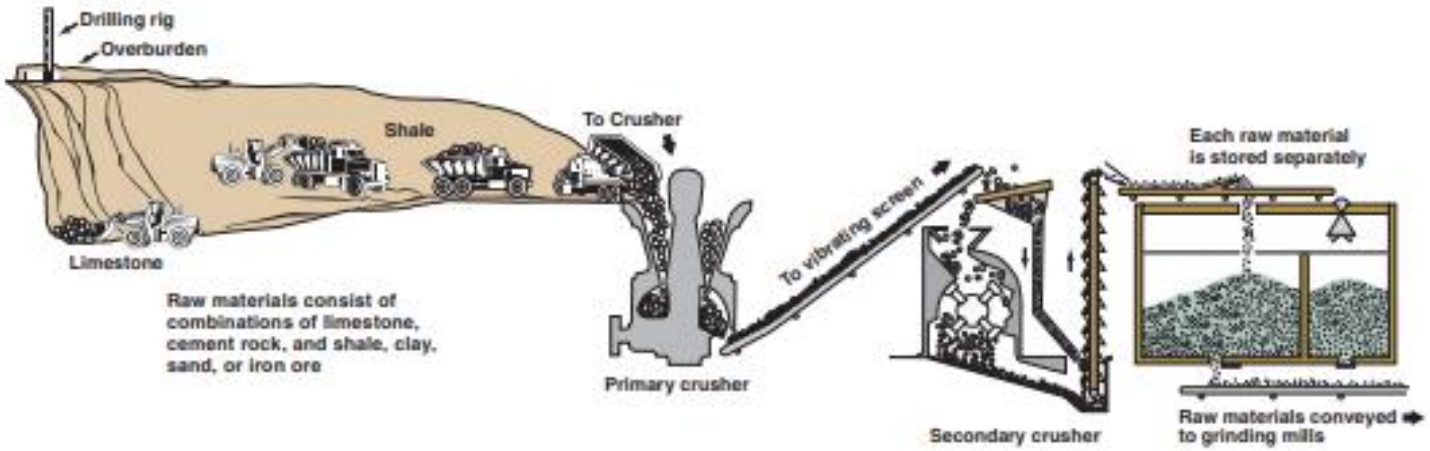


Figure 2.2. Raw materials are gathered and crushed in the first step of cement production (Kosmatka and Wilson, 2016).

Once the raw materials are in the grinding mills, they are ground even further to a fine powder, blended together, and sent to the kiln. This is shown in Figure 2.3.

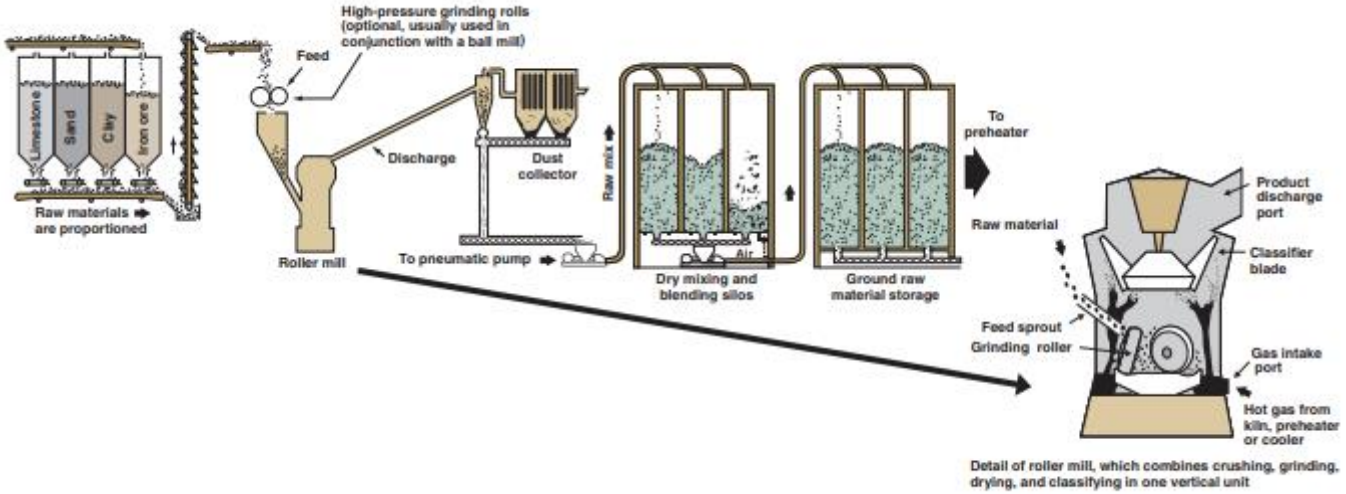


Figure 2.3. Raw materials are crushed further and sent to the kiln (Kosmatka and Wilson, 2016).

The next step in portland cement production is the heating process. This process consists of the raw powder being sent into a preheater followed by a rotating kiln. The kiln is where the calcium carbonate is calcined, and the materials react together to form clinker. The clinker is then cooled and stored before being conveyed to the last step. This is shown in Figure 2.4.

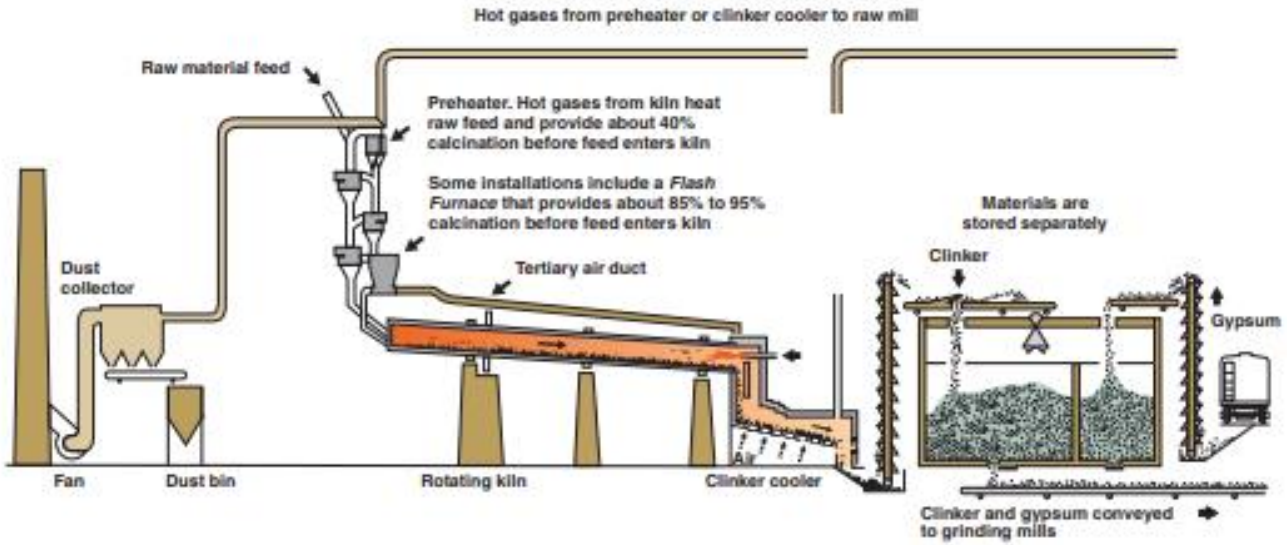


Figure 2.4. Raw materials are heated in a kiln, turned into clinker, and then cooled (Kosmatka and Wilson, 2016).

The last step of portland cement production involves taking the portland cement clinker and gypsum and grinding them together in a grinding mill. The reason gypsum needs to be added to portland cement clinker is because gypsum delays the setting time of portland cement and prevents a flash set. A flash set is when the cement paste hardens before it should. This last step is shown in Figure 2.5.

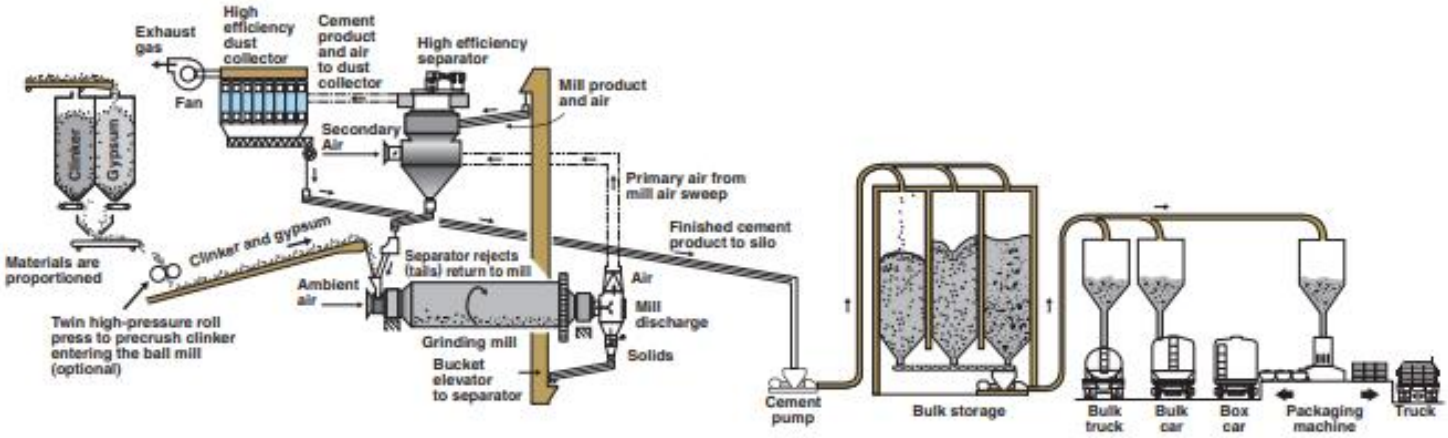


Figure 2.5. Clinker and gypsum are ground and mixed together (Kosmatka and Wilson, 2016).

Inside the kiln, material temperatures reach up to 1400-1500°C. During this 1-1½ hour process, the raw materials undergo a series of chemical reactions as the temperature increases. This is shown in Figure 2.6. When limestone ($CaCO_3$) heats up past 700°C, carbon dioxide (CO_2) and lime (CaO) are produced. The CO_2 is released into the atmosphere, while the CaO reacts with the SiO_2, Al_2O_3, and Fe_2O_3 from the other raw materials to form alite (C_3S), belite (C_2S), aluminate (C_3A), and ferrite (C_4AF); these make up the four primary phases in clinker. These phases along with gypsum are what make up portland cement.

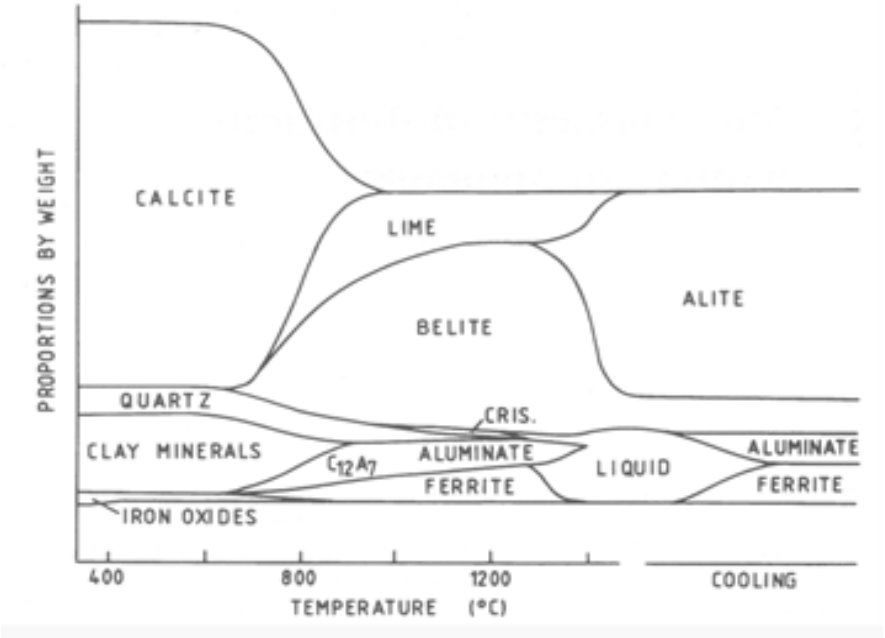


Figure 2.6. Formation of portland cement phases in the kiln (Taylor, 1997).

2.1.2.1 Hydration

When portland cement and water are mixed together to form a cement paste, a hydration process occurs causing these four phases to go through a series of chemical reactions.

The amount of water to portland cement is known as the water to cement ratio (w/cm). Each portland cement phase results in the formation of specific hydration products when combined with water and each of these hydration products contribute to the final properties of the concrete. C_3S, alite, is responsible for the initial set and early strength of the concrete. C_2S, belite, is most responsible for the ultimate, or later, strength of the concrete. C_3A, aluminate, is the phase that hardens the fastest and helps make the concrete more resistant to sulfates. C_3A is also the phase that can cause a flash set if clinker is mixed directly with water. To combat that, gypsum is added to the production of portland cement. Gypsum helps delay the setting time of the portland cement by binding with C_3A to form ettringite. C_4AF, ferrite, contributes little to strength and it is what causes concrete to be gray.

During the hydration of these phases, a large amount of heat is released called heat of hydration. The primary reactions that occur during hydration have to do with the reaction between the calcium silicates in the clinker and water. The two portland cement clinker phases, alite and belite, both hydrate to form calcium silicate hydrate (C-S-H) and calcium hydroxide (CH). C-S-H is responsible for the strength in concrete; it is considered the glue that holds everything together. CH on the other hand does not provide strength and can be harmful to the durability of the concrete. CH can initially help a mixture by filling in entrapped air-voids, making the sample more solid or dense. The issue with CH comes from how reactive it is with water. Once water reacts with CH, the entrapped air-voids that possibly could have been filled or made smaller during the curing process are now open again. This makes the concrete weak and less durable due to

these large opened entrapped air-voids. Therefore, it is important to find ways to decrease the amount of CH and increase the amount of C-S-H. To help form more C-S-H and increase the properties of a mixture, some of the portland cement can be replaced with a supplementary cementitious material. This is discussed further in the next section.

2.2 Pozzolanic Reaction

When a material rich in amorphous silica or alumina is used as a portland cement replacement, a pozzolanic reaction occurs. This means CH from portland cement hydration is turned into a secondary form of C-S-H. The reactivity of a pozzolan is determined from the pozzolan's chemical and mineralogical composition, size distribution of the particles, ratio of lime to pozzolan, water content, curing time, temperature, and if the material's structure is amorphous or crystalline (Walker and Pavía, 2011). During the pozzolanic reaction, C-S-H gel is being produced to help form a stronger bond since it is considered the glue that holds everything together. This is also where the CH is reacting with the silica and/or alumina from the pozzolan to form more C-S-H or calcium aluminate silicate hydrate (C-A-S-H) gel, making the concrete mixture even stronger. C-A-S-H gel is as strong and essentially the same as C-S-H gel except it includes alumina. CH alone contributes nothing to the strength of the concrete. The only thing CH does alone is help stabilize C-S-H by maintaining the high pH levels necessary (Kosmatka and Wilson, 2016). Equations representing the pozzolanic reaction are shown in Equation 1 through Equation 4.

$$C_3S + H \rightarrow C - S - H + CH$$
Equation 1. The hydration of alite results in C-S-H and CH

$$C_2S + H \rightarrow C - S - H + CH$$
Equation 2. The hydration of belite results in C-S-H and CH

$$CH + S + H \rightarrow C - S - H$$
Equation 3. Calcium hydroxide from the hydration of the calcium silicates combines with silica and water to form secondary C-S-H

$$\mathrm{CH} + \mathrm{A} + S + H \rightarrow C - \mathrm{A} - S - \mathrm{H}$$
Equation 4. When alumina is included, C-A-S-H can form

2.3 Supplementary Cementitious Materials (SCMs)

2.3.1 Pozzolans

SCMs are used with portland cement to help improve concrete properties while cutting down on the amount of portland cement needed. There are two types of reactions that can occur when SCMs are utilized: hydraulic or pozzolanic. An example of a hydraulic reaction is when a material high in CaO and SiO_2, like portland cement or Class C fly ash, reacts with water to form a cementitious phase. This phase development allows the mixture to bond together, form an ample amount of C-S-H gel, and make a strong concrete mixture. A pozzolanic reaction occurs when materials with a low CaO content and high silica (SiO_2) or alumina (Al_2O_3) content, such as Class F fly ash, metakaolin, or glass powder, are added to a portland cement mixture. C-S-H or C-A-S-H gel forms from the combination of silica and alumina and the remaining CH left over from the hydration reaction, as discussed in the last section. This helps the concrete become stronger and can enhance durability properties by reducing the permeability of the concrete. It is also important to note that the amount of water to portland cement and pozzolans is known as water to cementitious material (w/cm).

The term “pozzolan” originates back to Roman and Greek times when volcanic ash was mined at Pozzuoli, a village near Naples, Italy (Kosmatka and Wilson, 2016). The use of pozzolans dates back to ancient civilizations including the Romans and Greeks. The oldest known pozzolan, diatomaceous earth, dates back to 5000 BC, followed by the next oldest pozzolan reported, volcanic ash (ACI Committee 232, 2012). The addition of these pozzolans, with water and burned limestone, formed a hydraulic binder that helped keep the concrete durable and impermeable. Many other materials can also be used as pozzolans. These materials include some Class C fly ashes, Class F fly ash, metakaolin, silica fume, calcined shale, and glass powder. Figure 2.7 shows what these materials, excluding glass powder, look like in powder form.

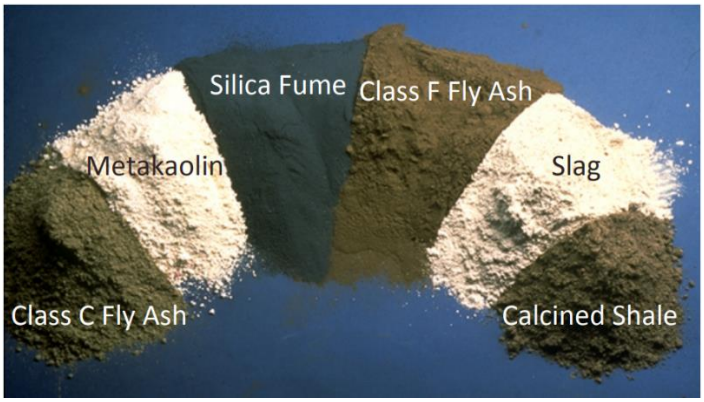


Figure 2.7. Visual of several types of pozzolans (Kosmatka and Wilson, 2016).

Pozzolans provide a solid market for many industrial byproducts that otherwise would end up in landfills. They also reduce the amount of portland cement in a concrete mixture, thereby reducing the carbon footprint. The proper use of pozzolans can improve the performance of concrete by enhancing specific properties. These properties can include reducing the permeability of the concrete or increasing the strength of the

concrete. The replacement level of a pozzolan used in a concrete mixture is dependent on the type, quality, and reactivity of the material. The reactivity is different for each pozzolan and plays a significant role in determining if the pozzolan will be successful or not.

2.3.2 Types of Pozzolans

As discussed in 2.3.1, there are many types of pozzolans that can be used in a concrete mixture to help enhance the concrete properties while lowering the amount of portland cement needed. Chemical composition examples of each pozzolan from Figure 2.7 are shown in Table 2.2. Each pozzolan affects the fresh and hardened properties of the concrete in different ways. Figure 2.8 and Figure 2.9 provide an overview of these effects.

Table 2.2. Chemical compositions of Type 1 portland cement and other pozzolans (Kosmatka and Wilson, 2016).

Chemical Composition, % by mass	Type 1 Portland Cement	Class F Fly Ash	Class C Fly Ash	Slag Cement	Silica Fume	Calcined Clay	Calcined Shale	Metakaolin
LOI (Loss On Ignition)	-	2.8%	0.5%	1%	3%	1.5%	3%	0.7%
SiO_2 (Silicon Dioxide)	19.8%	52%	35%	35%	90%	58%	50%	53%
CaO (Calcium Oxide)	63.3%	5%	21%	40%	1.6%	1%	8%	0.1%
Na_2O (Sodium Oxide)	0.62%	1%	5.8%	0.3%	0.5%	0.2%	-	0.05%
Al_2O_3 (Aluminium Oxide)	5.1%	23%	18%	12%	0.4%	29%	20%	43%
Fe_2O_3 (Iron (III) Oxide)	2.5%	11%	6%	1%	0.4%	4%	8%	0.5%
MgO (Magnesium Oxide)	2.3%	-	-	-	-	-	-	-
SO_3 (Sulfur Trioxide)	3.3%	0.8%	4.1%	2%	0.4%	0.5%	0.4%	0.1%
K_2O (Potassium Oxide)	-	2.0%	0.7%	0.4%	2.2%	2%	-	0.4%

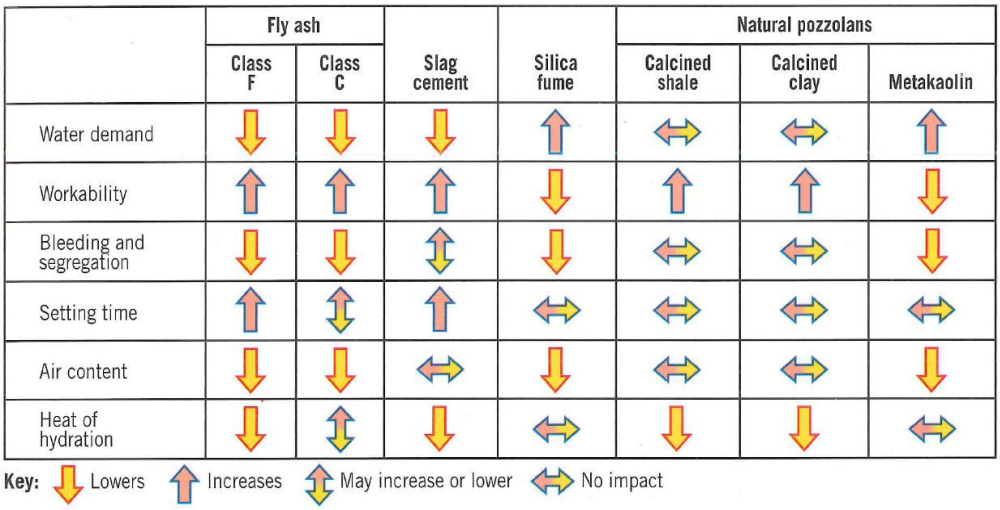


Figure 2.8. The influence of various pozzolans on fresh concrete properties (Kosmatka and Wilson, 2016).

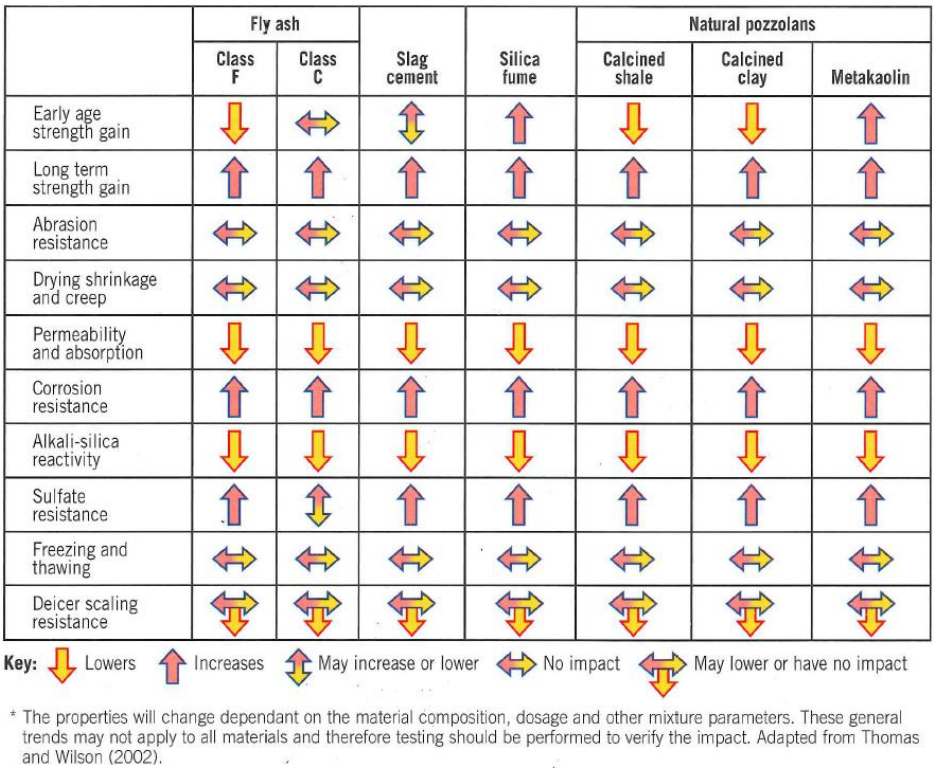


Figure 2.9. The influence of various pozzolans on hardened concrete properties (Kosmatka and Wilson, 2016).

2.3.2.1 Fly Ash

Fly ash is the most commonly used pozzolan. It is the byproduct of the combustion of pulverized coal in electric power generating plants (Kosmatka and Wilson, 2016). From this process, fly ash comes in two different forms: Class F and Class C. The difference between the two types lies primarily on the amount of calcium oxide (CaO), which depends on the type of coal used. Class F fly ash contains more silica and commonly replaces between 15-25% portland cement by mass, whereas Class C fly ash contains more calcium oxide and has a common replacement level between 15-40% by mass (Kosmatka and Wilson, 2016). There are many benefits to the fresh properties when fly ash is added into the concrete mixture. Typically, the water demand, bleeding and segregation, air content, and heat of hydration of the mixture decrease, while workability and setting time increase. These changes often lead to workable concrete that has a good flow with less water. It is important to reduce bleeding and segregation since this involves water raising to the surface while other materials, like aggregate, sink to the bottom. This leaves a weak portland cement paste at the surface and will cause water to evaporate faster resulting in shrinkage cracking. Air content, on the other hand, is something that should not be too high or too low. If the air content is too high, then there will be too many air voids resulting in weak concrete. If the air content is too low, then freezing water in the concrete will not be able to expand and shrink properly in freeze-thaw conditions, which can result in less durable and cracked concrete.

The hardened properties of concrete are also improved with the addition of fly ash. Concrete containing a pozzolan might have a slightly lower early strength as compared to

a 100% portland cement mixture but typically the long-term strength is ultimately higher. This means that concrete containing fly ash should be stronger than the concrete with just portland cement at later ages. The concrete with a pozzolan will also become less permeable to water and have a higher resistance to corrosion, sulfates, and alkali-silica reactivity. Overall, fly ash improves concrete properties and will continue being one of the most common types of pozzolans used in concrete mixtures.

2.3.2.2 Slag Cement

Slag cement, which is also known as ground granulated blast-furnace slag (GGBFS), is a byproduct that is formed from the production of iron used in steelmaking. To turn the molten slag into a cementitious material, it is rapidly cooled in water, dried, and then ground into a fine powder (Kosmatka and Wilson, 2016). By cooling it rapidly, it gets a glassy amorphous structure which allows the material to have both hydraulic and pozzolanic properties. There are three different grades of slag cement as found in ASTM C989 (2017): Grade 80, Grade 100, and Grade 120. The difference between the three is their activity index, which compares the compressive strength of a mortar cube with slag cement added versus a mortar cube with just portland cement. The higher the grade of the slag cement, the higher the activity index is. The replacement level for slag cement is typically between 30-50%, depending on its composition.

2.3.2.3 Silica Fume

Silica fume is the finest of all the pozzolans and is even finer than portland cement. Silica fume is a byproduct of the production of silicon metals and ferrosilicon alloys in electric-

arc furnaces. When the silica fume is cooled, it condenses and rises as an oxidized vapor from the furnaces and is collected in bag filters. It is then processed to remove impurities so that it can be used as a pozzolan (Kosmatka and Wilson, 2016). Silica fume contains a great deal of amorphous silica but is often limited to a replacement level of between 5-10% due to its extremely fine particle size distribution and low calcium oxide amount. A finer particle size indicates that the mixture will require more water. Without adding more water, the concrete would become less workable causing problems especially in situations where reinforcement is included.

Concrete containing silica fume typically has higher early strengths than concrete without. One quality that is always investigated in a pozzolan is how high its early and later strength activity indexes (SAI) are compared to a portland cement mixture. Early SAI is important because the sooner the concrete gains strength, the sooner construction can continue on a job site. Later strength is also important to ensure any hydration bonds formed early have either gotten stronger or stayed the same. It is possible for a mixture to have a high early strength but end up with a lower later strength. Ideally, the inclusion of a pozzolan would result in higher early or later strength and better durability as compared to a portland cement mixture. If these conditions can happen, more companies will want to include that pozzolan into their concrete mixture.

2.3.2.4 Metakaolin

Metakaolin is considered a natural pozzolan and originates from kaolin clay. When kaolin clay is heated at 750-850°C [1382-1472°F] for 1-2 hours in a furnace chamber, it

turns the kaolin into metakaolin (Moodi et al., 2011). Metakaolin is typically used as an additive to concrete rather than a replacement with around 10% of the portland cement mass being added. Metakaolin is used in applications where very low permeability or very high strength is needed (Kosmatka and Wilson, 2016).

2.4 Glass

Glass is a common material used in everyday products, but not every glass is the same. The glass used to make a windshield in a car or even a window for a house are considered the same glass type but are different than a glass bottle or a glass beaker. The common glass types include soda-lime (container and plate), borosilicate, lead, barium, aluminosilicate, and glass-ceramics. Not all glass is the same and the composition depends primarily on the application of the glass.

2.4.1 Soda-Lime Container Glass Production

Soda-lime glass can be divided into two categories: container glass and plate glass. Container glass is the most common type of glass made and recycled, and it includes glass used to make bottles and jars. Container glass is made of silica sand, soda-ash, limestone, and recycled glass (also known as cullet). These materials are combined and transferred in precise amounts into a furnace at temperatures of about 1500°C (2730°F). If the glass is supposed to be a certain color, sources of iron, sulfur, and carbon can be added to the melt. The furnace melts everything together, producing a cylindrical gob that is enough to make one glass bottle or jar. Each gob is then transferred to a bottle or jar

molding machine where it gets turned into a paracin; a miniature version of the final bottle. The paracin then gets moved into a blow mold where compressed air is pushed into it, stretching the glass outward to the mold forming the final bottle shape. Once the bottle leaves the forming machine, it moves through flames to ensure it does not cool down too quickly otherwise cracks will form. After the flames, a loader pushes the bottle into an annealing leer where it is cooled at a controlled level releasing the stress from the glass gradually. Following the annealing leer, the bottle is sprayed on the exterior with lubricant to help it move smoothly through the packaging and inspection line. The inspection line has machines that spin the bottles checking for impurities like cracks, proper dimensions, and the screw cap threads. The last inspection before packaging is a visual inspection by a person to ensure the bottle or jar is good to be shipped (Glass Packaging Institute). Figure 2.10 shows a diagram of the entire process.

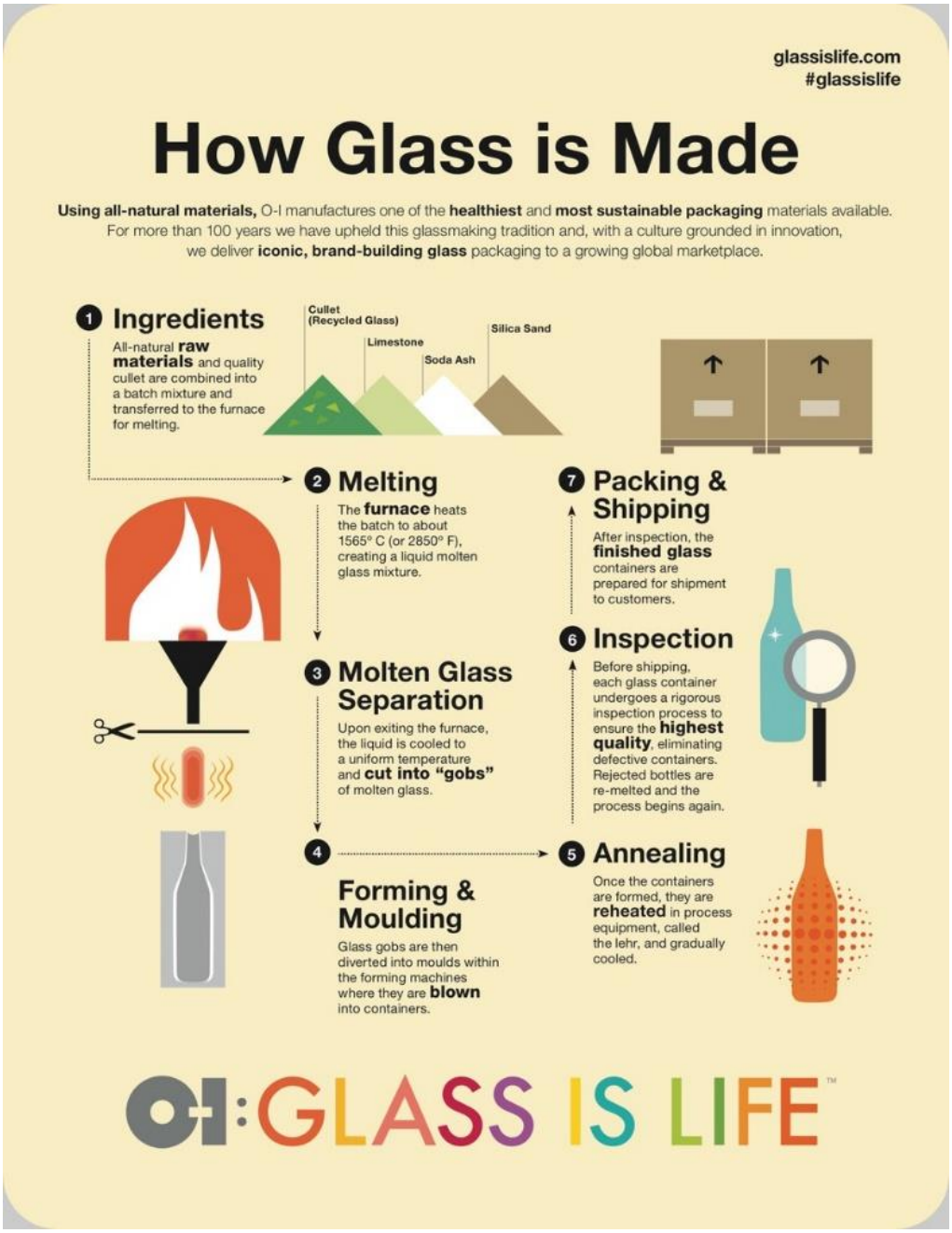


Figure 2.10. How glass bottles are made (Graphene).

2.4.2 Recycling and Collection of Soda-Lime Container Glass

Vo and Jiang (2013) wrote an article about how a used glass bottle becomes a new glass bottle and this is what they found. Once a container glass leaves the manufacturing plant, it is shipped to the proper destination to be filled, packaged, and shipped to stores. Once the container glass has been used, it is either thrown out or put into a recycling container to be collected; these containers can include curbside containers, bags, bins, or a recycling bank. On the consumer side, the glass is typically combined with paper, cardboard, metal, and plastics in single stream recycling programs. Trucks collect and bring the recyclables to a materials recycling facility (MRF) where it is piled outside and slowly moved into the facility. Inside the MRF, the recyclables go through various sorting processes to separate the glass first from the other recyclables and then from trash such as plastic bags, bottle caps, and various metals. The glass is then pushed through optical sorters that separate the glass based on its color. Color purity is important because only certain colors are useful for certain manufacturing processes. For example, clear glass could be used for jars and soda bottles, whereas darker colors could be used for wine and beer bottles. In any case, color purity tolerance is extremely low when the glass is used to make new glass. Once the glass is color separated, it is stored in separate color piles until it is ready to be shipped to the proper manufacturer. The crushed glass becomes known as cullet.

Recycling glass is beneficial to the environment. Glass can be recycled repeatedly without loss in quality or purity. Using recycled glass reduces the quantity of materials going into landfills and it saves on the amount of raw materials required to form new

glass since cullet can be melted and reformed. Another benefit of using recycled glass is that it lessens the demand for energy and CO_2 emissions. When it comes to the manufacturing of glass, for every six tons of recycled glass used, a ton of CO_2 is reduced. Energy costs also drop about 3% for every 10% of cullet used (Glass Packaging Institute).

2.4.3 Glass Properties and Composition

Even though soda-lime container glass is the most prevalent glass type out there, other types of glass make their way into the waste streams. These wastes streams could contain soda-lime plate, borosilicate, lead, barium, and aluminosilicate glasses. This research examined the following glass types: soda-lime container, soda-lime plate, aluminosilicate, glass ceramic, barium, phosphate, and E-Glass. Each glass type has their own use due to their varying properties. Soda-lime container glass is used to make bottles and jars, while soda-lime plate glass is used to make windows and windshields. Common terminology for windows is float and sheet glass. Phosphate glass is resistant to hydrofluoric acid, and with the addition of iron, it can be used to help dispose of radioactive waste. E-Glass is a type of glass fiber that falls under the aluminosilicate glass category. Glass fibers can be used as insulation or reinforcement in concrete. Glass-ceramics can resist repeated and quick temperature changes making it ideal to create stove tops, microwaves, and fireplace doors. Composition and examples of these glass types are shown in Table 2.3. Figure 2.11 shows a plot of the silica, calcia, and alumina contents of various pozzolans.

Table 2.3. Several types of glasses and their compositions (Shi and Zheng, 2007; Shelby, 2005).

Glasses and Uses (%)	SiO_2	Al_2O_3	B_2O_3	Na_2O	K_2O	MgO	CaO	BaO	PbO	Others
Soda-Lime Glasses										
Containers	66-75	0.7-7	-	12-16	0.1-3	0.1-5	6-12	-	-	-
Float (Plate)	73-74	-	-	13.5-15	0.2	3.6-3.8	8.7-8.9	-	-	-
Sheet (Plate)	71-73	0.5-1.5	-	12-15	-	1.5-3.5	8-10	-	-	-
Borosilicate										
Chemical Apparatus	81	2	13	4	-	-	-	-	-	-
Pharmaceutical	72	6	11	7	1	-	-	-	-	-
Lead Glasses										
Color TV funnel	54	2	-	4	9	-	-	-	23	-
Neon tubing	63	1	-	8	6	-	-	-	22	-
Electronic parts	56	2	-	4	9	-	-	-	29	-
Barium Glasses										
Color TV panel	65	2	-	7	9	2	2	2	2	10% SrO
Funnel	54	2	-	6	8	2.5	3.5	-	23	-
Aluminosilicate Glasses										
Combustion tubes	62	17	5	1	-	7	8	-	-	-
Fiberglass	64.5	24.5	-	0.5	-	10.5	-	-	-	-
E-Glass	52-56	12-16	5-10	0-2		0-5	16-25	-	-	0-0.8% Fe_2O_3
Glass-Ceramics										
Vision	68.8	19.2	-	0.2	0.1	1.8	-	0.8	-	2.7% TiO_2
Macor	47.2	16.7	8.5	-	9.5	14.5	-	-	-	-
White Sitall	55.5	8.3	-	5.4	0.6	2.2	24.8	-	-	0.3% Fe_2O_3

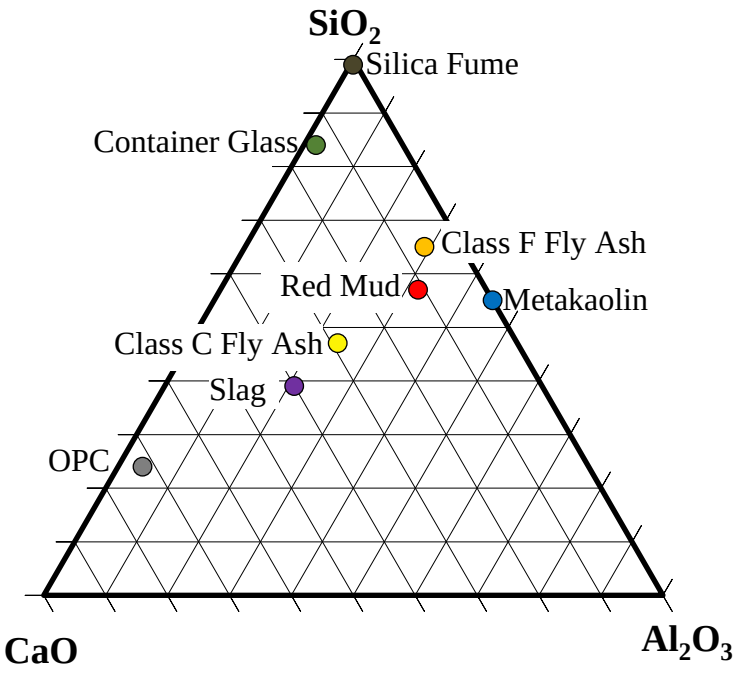


Figure 2.11. Compositions of different pozzolans compared to container glass.

2.5 Glass as a Pozzolan

2.5.1 Fresh Properties

Fresh property tests are typically performed when making mortar and concrete to get a better understanding of the mixture. These tests typically include slump or flow, air content, density, and temperature. Slump or flow gives an indication of the workability of the mixture and measures continuity between various batches. Fresh air content gives a preliminary indication of a concrete's ability to withstand freezing and thawing cycles. Temperature shows how hot the mixture got during the start of the first hydration phase. Density has been shown to increase with some replacement levels of glass powder

(Aliabdo et al., 2016). A higher density means a lower volume, and this can correlate with a stronger mixture.

2.5.1.1 Workability

Workability indicates how difficult the concrete is to place and how compactable the concrete is without any segregation. If the mixture has a high viscosity, that indicates it is thick and won't flow easily into tight locations like around rebar. Particle shape is an important trait to note about glass powder. When making mortar and concrete, the material's particle shape and size plays a key role in determining how much water is needed to obtain a certain flow or slump. Under a scanning electron microscope (SEM), glass powder particles are jagged just like portland cement particles but to a larger degree; they both come in assorted sizes as shown in Figure 2.12. This type of particle shape for glass indicates that it will be able to fill in pores indicating higher permeability to water and other chemicals. Aliabdo et al. (2016) noted a correlation between the glass powder replacement level and slump at the same water to cementitious material ratio (w/cm). As the replacement level increased, so did the concrete's slump. This indicates that using glass powder will decrease the amount of water needed to produce the same workability as a mixture with just portland cement. This could be due to the particle size of the glass, high specific surface area, the glassy surface on the glass particles, or the low absorption level that glass powder has (Aliabdo et al., 2016).

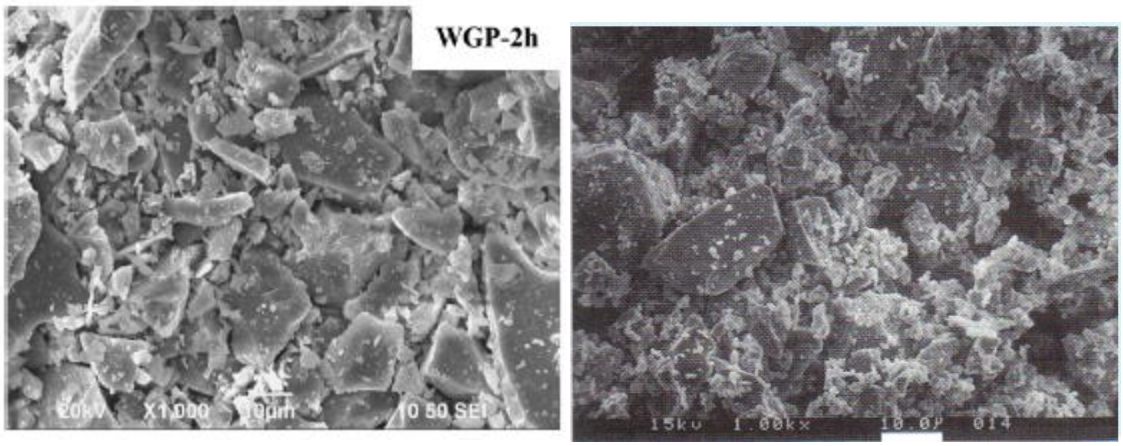


Figure 2.12. SEM of waste glass after two hours of grinding in a ball mill (Lu et al., 2017) (left) and SEM of powdered cement (Kosmatka and Wilson, 2016) (right) both at 1000x magnification.

2.5.1.2 Heat of Hydration

Heat of hydration is the increase or decrease in temperature when molecules from the cementitious material(s) start to react with the water molecules binding and forming new chemical compositions causing the mixture to set. The phases that are considered the most when it comes to hydration were discussed in 2.1.2.1 and include C_3S, C_2S, C_3A, and C_4AF. Heat of hydration is important to understand since the formation of these separate phases determine if the mixture will have a high early strength, high later strength, strong permeability, or other properties. At higher portland cement replacement levels with glass powder, it was observed that the heat evolution dropped (Shi and Zheng, 2007). Du and Hwee Tan (2015) also reported that replacing portland cement with glass powder reduced the early heat of hydration, and therefore typically resulted in a lower early strength. Kamali and Ghahremaninezhad (2016) contradict those findings by indicating that using glass powder actually enhanced the early hydration of their

mixtures. This again shows that not every glass is the same and that it is essential to understand the glass' properties.

Shi and Zheng (2007) noted that a mixture with a median particle size of 38μm at a 30% replacement exhibited enough high early and later strength to satisfy the minimum strength requirement of 75% found in ASTM C618 (2015). This contradicts other articles and indicates that not all glass, regardless of type, will react the same way. The reason this mixture could have done well compared to mixtures found in other articles could be due to the phases that formed. This article indicated that the production of calcium silicate hydrate (C-S-H) was found to be higher with the mixture containing glass powder. This means that the 38μm mixture had enough C-S-H formed at an early stage that the bonds were able to have a high strength. The strength of mixtures containing fine glass powders only increases with time due to the pozzolanic reaction (Kamali and Ghahremaninezhad, 2016).

2.5.2 Hardened Properties

When mortar and concrete mixtures have been made and cured for a certain amount of time, tests are performed to see how strong and durable they are. These tests can include compressive strength, flexural strength, freeze-thaw resistance, permeability, hardened air void analysis, and alkali-silica reaction (ASR) resistance. The purpose of doing these tests is to better understand how durable a concrete mixture will be in a given environment.

2.5.2.1 Compressive Strength

The compressive strength for mortar cubes is tested according to ASTM C109 (2016). These strength results are determined by various components, such as composition and particle size. Typically, glass will cause a pozzolanic reaction to occur due to its high silica and low calcia amounts. The glass' particle size can cause it to react differently in a mixture. The smaller the glass' particle size is, the more pozzolanic it will be and the quicker the glass will dissolve and react. The particle size, replacement level, and composition of the glass can make or break the mixture's compressive strength results. When the glass' particle size is below 100μm, pozzolanic reactivity will start to occur. This size at low replacement amounts can exhibit compressive strengths higher than fly ash after 90 days of curing (Khmiri et al., 2012). As noted in the same article, the mortar samples made with glass particles smaller than 40μm at a 20% portland cement replacement exhibited high enough compressive strength results to satisfy the minimum SAI of 75% at 7 days of curing. SAI is defined as the difference in strength from the control mixture sample to the glass sample. The control sample will always have a 100% SAI and any other sample that has a SAI over 100% indicates that it was stronger than the control sample at that break day.

Each article had their own optimal range for a portland cement replacement with glass powder to obtain a high compressive strength. Nassar and Soroushian (2011) states that with their soda-lime glass powder, a replacement level of 15-20% gave them compressive strengths exceeding the control mixture at 90 days. Their mixture of 23% replacement, however, did not exceed the control mixture at 90 days. Shayan and Xu's (2006) article

supported this by indicating from their 20 and 30% replacement results, only their 20% glass powder mixture met the SAI requirement. There have been studies done that disprove what the previous two articles state. Aliabdo et al's (2016) article states that with their soda-lime glass powder, anything over 10% decreases the compressive strength, whereas Du and Hwee Tan's (2015) article states that anything under 30% and over 45% lowers the compressive strength due to how the hydration phases form. The comparisons of these articles are shown in Table 2.4.

Table 2.4. Comparison of chemical composition and replacement level between different articles.

(Nassar and Soroushian, 2011; Shayan and Xu, 2006; Aliabdo et al., 2016; Du and Kiang, 2015)

Chemical Composition, % by mass	Nassar and Soroushian (2011)	Shayan and Xu (2006)	Aliabdo et al (2016)	Du and Hwee Tan (2015)
Replacement Levels	15-20%	20% & 30%	5-25%	15%, 30%, 45%, & 60%
Particle Sizes	25μm (Mean)	< 10μm (Nominal)	< 75μm	3.4μm (Mean)
Possible Glass Type	Soda-Lime Container	Soda-Lime Container	Soda-Lime Container	Soda-Lime Container
LOI (Loss On Ignition)	-	-	0.82%	-
SiO_2 (Silicon Dioxide)	73.50%	72.40%	71.40%	72.08%
CaO (Calcium Oxide)	9.20%	11.50%	11.20%	10.45%
Na_2O (Sodium Oxide)	13.20%	13.00%	12.25%	13.71%
Al_2O_3 (Aluminum Oxide)	0.40%	1.45%	2.54%	2.19%
Fe_2O_3 (Iron (III) Oxide)	0.20%	0.48%	0.37%	0.22%
MgO (Magnesium Oxide)	3.30%	0.65%	1.60%	0.72%
SO_3 (Sulfur Trioxide)	-	0.09%	0.16%	-
K_2O (Potassium Oxide)	0.10%	0.43%	0.36%	0.16%
TiO_2 (Titanium Dioxide)	-	-	-	0.10%
Cr_2O_3 (Chromium (III) Oxide)	-	-	-	0.01%

2.5.2.2 Alkali-Silica Reaction (ASR) Mitigation

Alkali-silica reaction (ASR) is a reaction that occurs in concrete when the alkalis in portland cement react with the silica found in glassy, siliceous (or reactive) aggregates. This reaction causes a gel to form that expands and causes serious cracking in the

concrete. This cracking causes the concrete to have lower strength and durability properties. Figure 2.13 shows an example of ASR in concrete. Alkali-silica reaction tests can be found in ASTM C1260 (2014) and ASTM C1567 (2013).

Figure 2.13. Example of ASR on a concrete step barrier (Federal Highway Administration (FHWA), 2006).

When glass is used in a concrete mixture, its particle size plays a significant role in determining if ASR will occur or not. Shi and Zheng (2007) found that glass ground to a powder, finer than 300μm and used as a pozzolan, will not generate deleterious expansion especially as the replacement level increases. This happens because the pozzolanic reaction of the fine glass powder occurs on the glass surface (Du and Hwee Tan, 2015). If the glass particles are large and used as an aggregate versus as a pozzolan, the mixture will see ASR occur due to the silica in the glass reacting with the alkalis in the portland cement. This indicates that unless another mitigation technique is used with the glass aggregate to suppress ASR, glass is more beneficial to use as a finely ground powder.

This topic is still being investigated and this research does not further expand on this topic. A microstructural view of concrete afflicted with ASR is shown in Figure 2.14.

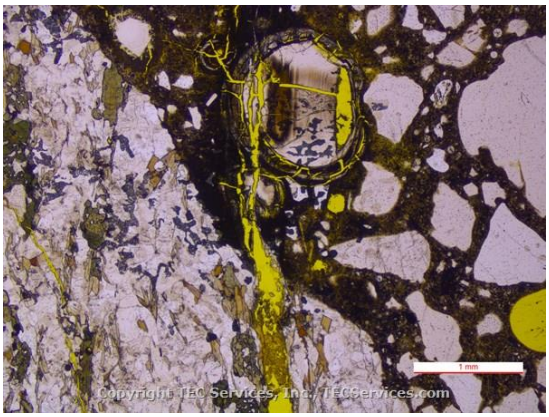


Figure 2.14. Microstructure of concrete with formed ASR gel (Wolfe).

2.5.2.3 Hardened Air-Void Structure

Freezing and thawing is a type of physical weathering that occurs in colder climates. When water inside of a material freezes, it ends up occupying 9% more volume than before causing the material to experience high levels of stress. In a material like concrete, water will occupy its pores. The expansion of freezing water can be dealt with if the pores are properly formed and are uniformly spread throughout the concrete. A good pore system causes the concrete to be durable enough not to fail. If the concrete cannot handle the expansion of the freezing water, cracks will start to form indicating that concrete is starting to fail. Once cracks form and the ice start to thaw, water and chlorides will infiltrate the cracks causing rebar inside the concrete to corrode and hydration phases and products inside the concrete to possibly break apart. If it is cold enough for the water to freeze again, it will cause these cracks to grow until the concrete completely breaks and

fails. The combination of rebar corroding, possible harm to hydration phases and products, and continuous concrete cracking is a disaster waiting to happen. Therefore, freeze-thaw resistance is an important property to measure especially when adding various materials into a concrete mixture. A good start to examining freeze-thaw resistance is starting with the mixture's hardened air-void structure.

The distribution and size of the air voids are known as the hardened air void structure. The likelihood of damage from freezing and thawing can be predicted by examining the hardened air-void structure within the concrete. Several types of voids exist and include gel pores, capillary voids, and air voids. Gel pores, also known as interlayer hydration space, are the smallest of the voids having sizes range from 10nm to less than 0.5nm. They are spaced between layers in C-S-H and act as a paste, but have insignificant impact on strength, permeability, and shrinkage. Capillary voids are the next largest void with sizes ranging from 10,000nm to 10nm. These voids are space that use to be filled with water between partially hydrated portland cement grains. The larger voids affect strength and permeability and the smaller voids affect shrinkage. Air voids are the biggest type of void and they can be broken into two different types: entrained air and entrapped air (Kosmatka and Wilson, 2016). Entrained air forms voids that are smaller than entrapped air and is almost spherical in shape. It is added into concrete as an admixture and is uniformly distributed but not interconnected within the concrete. Finally, it helps increase the durability in concrete by providing freeze-thaw resistance due to these voids absorbing the pressure created from the expansion of freezing water. Entrapped air involves voids that are large and irregularly sized, which does not help combat freeze-

thaw. These voids are formed from improper mixing, consolidation, and placement of the concrete but can be fixed with proper vibrating techniques (Goguen, 2012). In short, entrained air is good, while entrapped air is bad for concrete.

One way to mitigate the damage caused by freezing and thawing is by adding admixtures like an air-entrainer. Air entraining admixtures (AEAs) help form well distributed and small air voids that can enhance the hardened air-void structure. Examining the void structure within concrete is important as the frequency and size of the voids determine how effective the transport of liquids and gases will be, which relates to freezing and thawing resistance.

Permeability is the ability of the concrete to resist penetration by liquids. When using glass powder as a pozzolan, it has been noted that glass powder reduces the penetration amount of chlorides and water in the concrete (Du and Hwee Tan, 2015). The reduction in how permeable the concrete is occurs from a strong air-void structure. Sorptivity, which is the ability of the unsaturated specimen to absorb and transmit water due to capillary voids, has also seen a decrease with the increase of glass powder (Du and Hwee Tan, 2015). This is due to the refined microstructure, improved pore network, filling effect of glass particles, and a less porous, denser interfacial transition zone (ITZ) from the pozzolanic reaction of the glass powder. This pozzolanic reaction creates more C-S-H that ends up filling pores and decreasing the porosity of the glass powder concrete (Omran and Tagnit-Hamou, 2016; Du and Hwee Tan, 2015; Al-Akhras, 2012). This indicates that a mixture containing glass powder will need a smaller w/cm ratio, as

compared to a portland cement mixture, to produce the same consistency and higher resistance to freeze-thaw damage.

When investigating the performance of a new pozzolan, the hardened air-void structure is an important parameter to consider. This is because the hardened air-void system is a key indicator of the freeze-thaw resistance of a concrete mixture. The use of ground glass in concrete could lead to a unique issue when it comes to freeze-thaw durability; this is due to the glass powder having the possibility of introducing soap into the mixture. As explained earlier, soap can get on the glass while it is in the recycling or trash. It is possible that soap can affect the entrained air voids by causing a film to appear around them and not allowing these voids to work properly. The soap can also cause the formation of entrapped air voids or form an unstable air void system that can be measured in fresh property tests but disappears when the concrete hardens. Understanding the contaminants on the glass is essential for constructing a good mixture.

ASTM C457 (2016) provides three different tests that can be used to analyze the hardened air-void structure. By performing one of these tests, it will provide beneficial information about how durable the sample is. Understanding how and why the air voids formed is essential to figuring out a way to enhance the mixture's durability and other properties. An example of a picture taken from a hardened air-void test is shown in Figure 2.15.

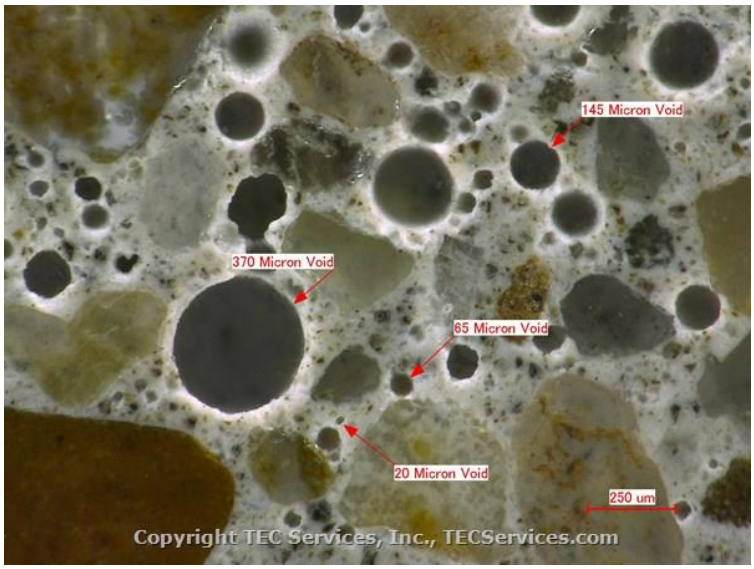


Figure 2.15. Example of hardened air voids (Wolfe).

3 Methods and Materials

3.1 Research Phases

This research included two phases. Phase I compared the replacement level and compressive strength of fourteen different glasses mixtures to a portland cement mixture and a Class F fly ash mixture. Phase II included four more glasses to help compare with the original fourteen glasses from Phase I. This phase also included the hardened air-void test and microstructure examination between the portland cement mixture, three glass mixtures at 20% replacement, and Class F fly ash at 20% replacement. Going into these phases, the hypothesis was that the mixtures with the largest SiO_2+Al_2O_3+Fe_2O_3 percentage would result in larger strength values due to more C-S-H or C-A-S-H forming from the pozzolanic reaction and the samples with a weak compressive strength and poor air-void structure could be due to having a high level of bad contaminants.

3.1.1 Phase I

The first phase of this research involved running compressive strength tests on fourteen different glass mixtures at 20 and 30% replacement levels and comparing them to a Class F fly ash mixture at the same replacement levels and a portland cement control mixture. Compressive strength testing is a mechanical test that indicates how much a material can handle before fracturing; this provides the material's specific strength ($f'c$). For these thirty-one mixtures, this test occurred on 1, 7, 28, 56, 90, and 182.5 with three cubes to break for each mixture per break day.

The glasses came from multiple wastes streams and were categorized using the alphabet for simplicity. The glasses used in this phase are identified as A, B, C, D, E, G, H, J, K, L, M, P, Q, and R. B and C are container and plate glasses. L, R, and V are a soda-lime plate glass. D is an aluminosilicate glass and glass ceramic. H is a TV/CRT panel (barium) and soda-lime container glass. P is a phosphate and soda-lime container glass. Q is an E-glass. The rest of the glasses remaining for this phase are soda-lime container glasses.

3.1.2 Phase II

With soda-lime glass making up a significant percentage of the waste glass stream, over 80% (Shi and Zheng, 2007), it was used to further expand on this research. This phase dealt with the compressive strength of four more glass samples and the examination of the hardened air-void structure of five different samples. The new glass samples S, T, V, and X were used to examine and add more data to the compressive strength test, while portland cement, Class F fly ash, and samples Q, S, and T were used to examine the hardened air-void structure and microstructure. Glass X is soda-lime container glass that was placed in a bottle collection can. This means soap and other contaminants usually found in recycling and trash containers along with different glass types did not encounter this glass sample. S and T are from a material recycling facility (MRF) and they are a soda-lime container glass that was mixed with other trash and recyclables. The difference between the two is that glass T has not gone through the recycling plant yet and it is still mixed with other materials making it dirty, while S has gone through the facility's

cleaning process. Glass V is a soda-lime plate glass that should not contain any surface contaminates.

2”x2”x2” mortar cubes were made for both compressive strength and hardened air-void tests. Compressive strength was tested on 1, 7, 28, 56, 90, and 182.5 days with three cubes to break for each mixture per break day. Extra cubes were made for each sample and three cubes each from the portland cement, Class F fly ash, and Q, S, and T samples were saved and prepared to examine the hardened air-void structure. The hardened air-void test was performed using Procedure C: Contrast Enhanced Method found in ASTM 457 (2016), and it helped obtain information on how the samples’ durability and how they would possibly perform under a freeze-thaw test. This procedure involves taking the sample and cutting it in half allowing one half to get prepared for the hardened air-void analysis and the other half to either be saved as a backup or discarded. Following this method allowed for the other half of each of these 5 samples to be used for microscopy examination. Microscopy involves using a scanning electron microscope (SEM) to look at the formed structure of a fractured or polished surface along with the ability to examine the composition of chosen locations. The curing age of these cubes included the control sample at 300 days, Class F fly ash sample at 299 days, sample Q at 289 days, and samples S and T at 197 days. As per ASTM 457 (2016), when using No. 4 aggregate, which the silica sand was in this research, the minimum area required to examine is 7 in^2. Due to some complications that will be discussed further in Section 3.3.3, the 3”x6” mortar cylinders were disposed of and 2”x2”x2” mortar cubes were used in their place, which is why there is a variance in curing ages. After 90 days of samples curing, almost

all of the hydration products have formed, so it was not an issue to have this wide range of curing ages.

3.2 Materials

3.2.1 Portland Cement and Fly Ash

For the control mixture, Type I portland cement with 90% (D90) of its mass being smaller than 37μm was utilized. Class F fly ash was used in this research to compare to the glass powder mixtures due to its popularity as a good pozzolan. The fly ash used had 90% of its particles smaller than 56μm. All the compositions were found using x-ray fluorescence (XRF). The composition of portland cement and fly ash are shown in Table 3.1, while Figure 3.1 shows what an XRF looks like.

Table 3.1. Composition of the cement and Class F fly ash used in this research.

Chemical Composition, % by mass	Type 1 Portland Cement	Class F Fly Ash
LOI (actual)	-	0.70
SiO_2 (Silicon Dioxide)	23.1	54.81
CaO (Calcium Oxide)	64.6	12.56
Na_2O (Sodium Oxide)	-	1.47
Al_2O_3 (Aluminum Oxide)	4.19	16.77
Fe_2O_3 (Iron (III) Oxide)	2.58	5.91
MgO (Magnesium Oxide)	1.27	4.29
SO_3 (Sulfur Trioxide)	2.89	0.54
K_2O (Potassium Oxide)	0.63	2.73
TiO_2 (Titanium Oxide)	0.26	0.65
P_2O_5 (Phosphorus Pentoxide)	0.14	0.20
ZnO (Zinc Oxide)	-	0.01
Mn_2O_3 (Manganese (III) Oxide)	0.05	0.06
Cr_2O_3 (Chromium (III) Oxide)	-	0.02
SrO (Strontium Oxide)	0.20	0.25

Figure 3.1. Rigaku XRF machine used to determine composition of samples.

3.2.2 Glass

Glass of assorted sizes and waste streams were obtained from numerous glass recycling facilities around the United States. This research focused on eighteen different glass

sources from nine different states to help give this research various compositions to look at. Each glass was given a letter from the alphabet to easily identify them. They were also placed in a large plastic drum and sealed tight to prevent contamination. All information about each glass used was provided by the source.

ASTM C618 (2015) is the standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. Classification and properties needed to make an acceptable pozzolan are found within this specification and are broken between three classes: Class F, Class C, and Class N. Class F and Class C relate just to fly ash. Class N relates to raw or calcined natural pozzolans; this is what glass powder falls under. Chemical and physical requirements for Class N should be met to make it effective in concrete. For Class N, the chemical requirements are that $SiO_2+Al_2O_3+Fe_2O_3 \geq 70\%$, $SO_3 \leq 4\%$, moisture content $\leq 3\%$, and loss on ignition (LOI) $\leq 10\%$. From all the glass samples used, glass H was the only sample that did not meet one of the requirements. Glass H had a $SiO_2+Al_2O_3+Fe_2O_3 = 67.6\%$ instead of 70% or greater. This glass was still tested to have another sample to compare compositions with. Table 3.2 shows the relevant compositions for each pozzolan to indicate how they compare to what ASTM C618 (2015) requires. This data can be relevant in comparing why some samples did better than others.

Table 3.2. Relevant elemental compositions of samples for comparison to what ASTM C618 (2015) requires.

Sample	CaO (%)	$SiO_2+Al_2O_3+Fe_2O_3$ (%)	$Na_2O_{(eq)}$ (%)	SO_3 (%)
PC	64.60	29.87	0.69	2.89
A	11.34	74.90	11.34	0.12
B	7.96	73.99	12.29	0.22
C	8.58	73.73	11.00	0.20
D	7.56	79.02	5.61	0.06
E	11.13	74.57	10.77	0.09
G	11.51	74.60	11.08	0.10
H	6.87	67.63	10.99	0.12
J	10.12	74.88	11.67	0.18
K	11.49	75.62	10.73	0.08
L	9.82	73.37	11.41	0.25
M	11.44	74.92	11.20	0.11
P	6.34	73.89	10.89	0.15
Q	21.90	74.30	0.84	0.03
R	10.04	72.51	11.17	0.24
S	10.02	71.90	11.81	0.10
T	9.00	70.60	13.46	0.10
V	8.72	72.96	12.61	0.20
X	9.89	72.06	15.83	0.16
FA2	12.56	77.49	3.27	0.54

The only thing considered in ASTM C618 (2015) for the physical requirements of these classes was that the strength activity index (SAI) was greater than or equal to 75% at both 7 and 28 days. SAI is the comparison between the test sample to the control sample. If the SAI is over 75%, it means that, in terms of compressive strength, the mixture design used for the test sample is acceptable to use in concrete. When the SAI is larger than 100%, it means that the test sample's compressive strength outperformed the control sample's compressive strength.

A crucial factor when using any material, especially glass, as a pozzolan is its particle size distribution (PSD). Based on the information discussed in Sections 2.4 and 2.5, the particle size for glass powders should be less than 45µm to have a pozzolanic effect. Based on the literature, it was decided that the particle size used in this research should have at least 90% (D90) of the glass powder passing 45µm, a median particle size (D50) between 8-14µm, and at least 10% (D10) between 1.5-2.5µm (Shao and Lehoux, 2001; Taha and Nounu, 2009; Schwarz and Neithalath, 2008). Since the glasses arrived in sizes ranging from very coarse to very fine, particle sizes needed to be found to determine which ones needed to be ground further. A laser particle size analyzer was utilized for this and is shown in Figure 3.2.

Figure 3.2. Laser Particle Size Analysis equipment 1180 by CILAS used to find glass powder particle sizes.

Any glass that needed to be ground further was ran in a ball mill with steel ball charge sizes of ½", ¾", and 1 ¼". The ball mill is shown in Figure 3.3.

Figure 3.3. Ball mill used to grind glass powder to finer sizes.

During the grinding process, PSDs were taking after certain periods until the glass powder met our targeted size. The PSD values for D10, D50, and D90 (10% passing, 50% passing, and 90% passing) of all the materials used are shown in Table 3.3.

Table 3.3. Corresponding particle sizes for each sample.

Name	% Passing, final sizes		
	D90	D50	D10
Silica Sand	552.05	344.41	200.57
PC	37.19	19.26	4.45
FA2	56.56	13.61	1.72
A	45.68	14.93	2.55
B	31.79	10.83	2.11
C	30.19	10.31	2.33
D	30.22	10.70	2.09
E	33.17	12.56	2.33
G	34.38	12.33	2.28
H	37.66	10.06	1.83
J	46.79	11.38	1.91
K	39.24	12.12	2.20
L	36.08	10.04	1.85
M	31.83	11.59	2.18
P	39.90	13.23	2.26
Q	26.69	10.72	1.85
R	24.33	9.27	2.03
S	34.64	12.80	2.40
T	27.92	8.11	1.64
V	2.20	10.63	31.82
X	2.16	12.33	35.63

Once all the glass was ground to the correct size, x-ray fluorescence (XRF) was run to determine the elemental weight composition of percent oxide for each glass. The visual and numerical oxide composition values are shown in Figure 3.4 and Table 3.4 respectively.

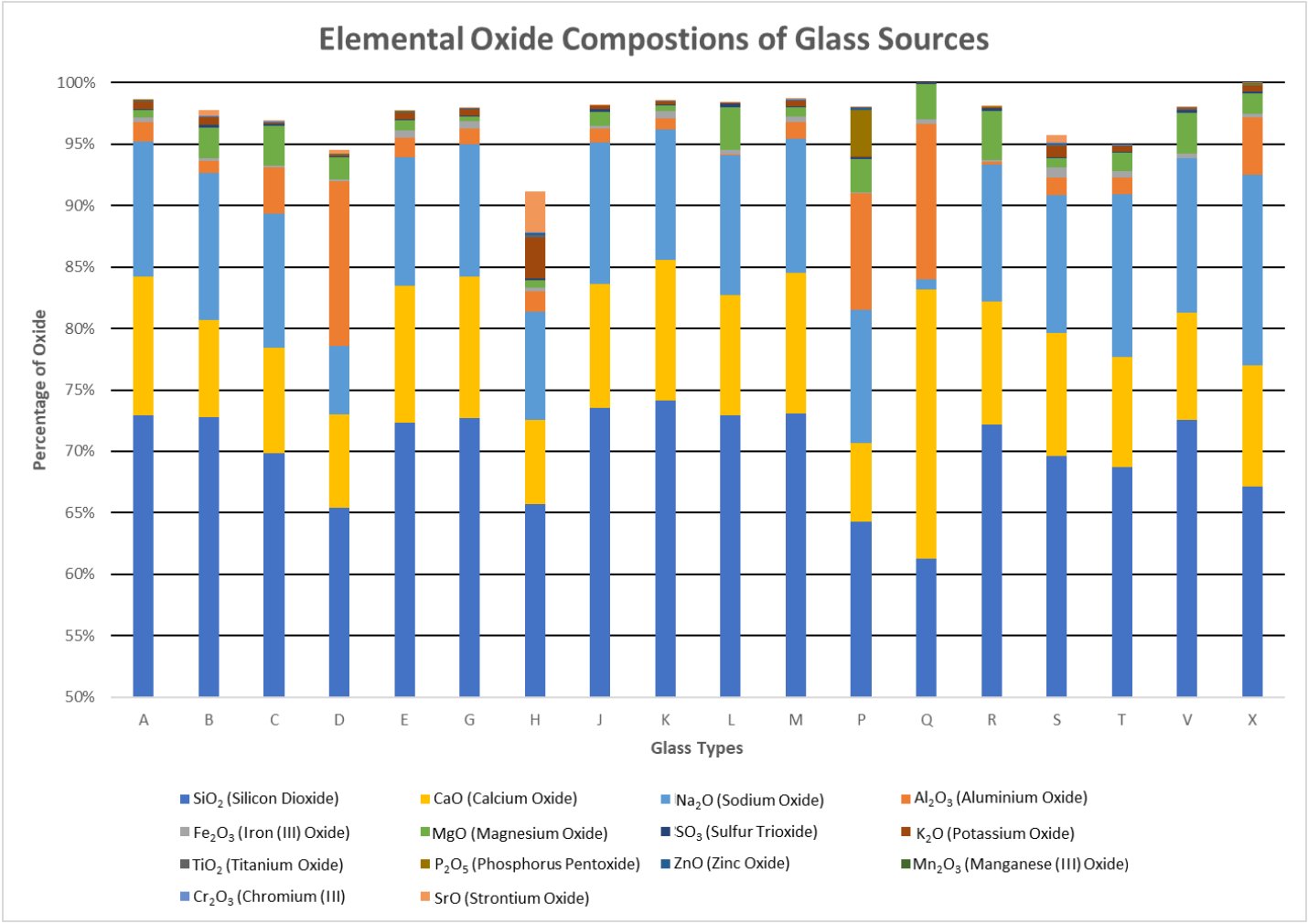


Figure 3.4. Visual composition percent by mass values for 18 different types of glasses.

Table 3.4. Composition by weight percent oxide for glasses used in this research.

Composition (% by mass)	LOI	SiO_2	CaO	Na_2O	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	TiO_2	P_2O_5	ZnO	Mn_2O_3	Cr_2O_3	SrO
A	0.55	72.91	11.34	10.94	1.61	0.38	0.57	0.12	0.61	0.05	0.02	0.01	0.01	0.05	0.02
B	0.97	72.76	7.96	11.91	0.98	0.25	2.51	0.22	0.58	0.04	0.05	0.02	-	0.01	0.51
C	1.39	69.83	8.58	10.95	3.77	0.13	3.21	0.20	0.08	0.03	0.03	0.01	-	0.01	0.02
D	0.64	65.42	7.56	5.58	13.45	0.15	1.80	0.06	0.05	0.11	0.05	-	-	0.01	0.31
E	1.22	72.33	11.13	10.44	1.60	0.64	0.79	0.09	0.50	0.07	0.03	0.02	0.02	0.04	0.02
G	0.69	72.73	11.51	10.78	1.25	0.62	0.36	0.10	0.46	0.05	0.02	0.01	0.01	0.03	0.01
H	1.05	65.71	6.87	8.81	1.59	0.33	0.64	0.12	3.31	0.23	0.03	0.14	0.01	0.02	3.30
J	0.58	73.52	10.12	11.47	1.15	0.21	1.17	0.18	0.31	0.03	0.02	-	-	-	0.01
K	0.64	74.11	11.49	10.60	0.90	0.61	0.46	0.08	0.20	0.05	0.02	-	0.02	0.01	0.01
L	0.64	72.90	9.82	11.36	0.11	0.36	3.47	0.25	0.07	0.03	0.01	-	-	-	0.01
M	0.57	73.07	11.44	10.90	1.35	0.50	0.70	0.11	0.46	0.04	0.02	0.01	0.01	0.03	0.01
P	0.46	64.31	6.34	10.86	9.50	0.08	2.69	0.15	0.04	0.02	3.76	0.27	-	-	0.03
Q	1.33	61.30	21.90	0.81	12.64	0.36	2.88	0.03	0.05	0.90	0.07	-	-	0.02	0.02
R	1.53	72.16	10.04	11.14	0.24	0.11	4.00	0.24	0.04	0.02	0.08	0.01	-	-	0.01
S	0.10	69.63	10.02	11.18	1.41	0.86	0.72	0.10	0.95	0.12	0.02	0.05	0.01	0.09	0.55
T	0.10	68.70	9.00	13.20	1.40	0.50	1.50	0.10	0.40	0.10	0.00	-	-	0.10	-
V	0.06	72.56	8.72	12.55	-	0.40	3.34	0.20	0.09	0.11	0.01	0.01	0.01	0.01	0.01
X	-	67.10	9.89	15.50	4.66	0.30	1.66	0.16	0.50	0.05	0.06	0.02	0.03	0.04	0.02

The glasses obtained had information and their identification provided by the source. To ensure accuracy and to obtain a better understanding of each glass sample, further analysis was completed. Looking at the final XRF composition data and comparing it to different sources (Shi and Zheng, 2007; Shelby, 2005), a decision was made as to what each glass sample was. The final analysis is shown in Table 3.5.

Table 3.5. Identification of glass with their corresponding waste stream.

Glass ID	Waste Stream, Type, and Extra Information
A	Consumer, Soda-Lime Container
B	Consumer, Soda-Lime Container and Plate
C	Consumer, Soda-Lime Container and Plate
D	Industrial, Aluminosilicate Glass and Glass Ceramic
E	Consumer, Soda-Lime Container
G	Consumer, Soda-Lime Container
H	Consumer, TV/CRT Panel (Barium) and Soda-Lime Container
J	Consumer, Soda-Lime Container
K	Consumer, Soda-Lime Container
L	Consumer, Soda-Lime Plate
M	Consumer, Soda-Lime Container
P	Industrial and Consumer, Phosphate and Soda-Lime Container
Q	Industrial, Aluminosilicate, E-Glass
R	Consumer, Soda-Lime Plate
S	Consumer, Soda-Lime Container, Clean, Not Treated
T	Consumer, Soda-Lime Container, Not Clean, Not Treated
V	Consumer, Soda-Lime Plate
X	Consumer, Soda-Lime Consumer, Drop-Off

3.2.3 Silica Sand

Silica sand was used in this research to make mortars. This silica sand met the specifications found in ASTM C778 (2013).

3.3 Mixture Design and Procedure

3.3.1 Mixing Procedure

Mixing procedures followed ASTM C109 (2016) and a modified version of ASTM C457 (2016) for all the 2”x2”x2” mortar cubes. Room temperature tap water, Type I portland cement, and 40/70 silica sand was used in correlation with the glass powder and Class F fly ash to make the mortar cube samples. All mortar cubes were cured for 24 hours in a humidity chamber before being demolded and returned to the chamber until their test day.

To properly replace portland cement, the portland cement and glass powder or fly ash were weighed separately and mixed together before being added to the mixer. This ensured that all the cementitious materials were properly blended together. The mixtures included portland cement, a pozzolan (if not the control mixture), silica sand, and room temperature tap water. The start of the mixing process included taking the water and cementitious material and adding them to the mixer to be mixed for 30 seconds on slow speed. After 30 seconds the aggregate was then added into the mixture and was left on slow speed for an additional 30 seconds followed by 30 seconds on medium speed. Once the final 30 seconds finished, the mixture sat in the bowl for 1 minute 30 seconds to help it set. During this time, the mixing paddle and mixing bowl were scraped clean to ensure all the materials were being properly mixed in. When the time ran out, a final minute of mixing on medium speed occurred. After the final minute, fresh properties were measured, and samples were made in the plastic cube molds. The mixer and some of the cube molds used are shown in Figure 3.5.

Figure 3.5. Hobart A-20C mixer used to make all test samples.

3.3.1.1 Fresh Properties

When the final minute of mixing was up, it was crucial that the temperature, flow, and unit weight were taken. Testing the temperature of each mixture helped show how hot the mixture was getting during the initial steps of the hydration process. The flow test, which is in ASTM C1437 (2016), helped show the workability of the mixture for a certain w/cm ratio. In ASTM C311 (2016), running the flow test was a requirement to ensure that all the pozzolan mixtures had a flow within ±5% of the portland cement control mixture. This is to ensure that all mixtures are made with consistent workability. It was observed, for the most part, that as the replacement of glass powder increased, the water demand decreased. This could be due to some things such as contaminants, like soap, an

improved pore structure, or a filling effect from the glass particles. Unit weight is needed to get the density of the mixture. Density helps determines the solidity of the concrete and plays a role in compressive strength.

For both phases, temperature was taken with a temperature probe at three different locations while the mixture was still in the mixing bowl. The three temperatures were recorded, and the average was found for each mixture. Flow test, which is shown in Figure 3.6, was done by getting the flow table and mold damp, filling the mold with two lifts, with each lift being tamped 20 times, and smoothing the top of the mold off with a trowel. The flow table was then cleaned off and dampened around the mold to ensure the mixture had a clean, damp surface to move on. The mold was removed, and the flow table was immediately dropped 25 times in 15 seconds. Calipers were used to measure the diameter of the dropped mixture at four locations on the flow table. After equations from ASTM C1437 (2016) were completed, the result gave the flow in percent. If this value was within ±5% of the control mixture, the mixture, including what was used on the flow table, was mixed for another 15 seconds on medium speed. If the result was not within ±5% and the mixture was too wet, it was thrown away and a new mixture was started. If the mix was too dry, a measured amount of water was added, and the mixture was remixed for 15 seconds. The flow test was repeated until it passed for that mixture. Unit weight involved taking three 2”x2”x2” mortar cubes, zeroing the scale with a cube mold, filling the cube molds with the mortar mixture, and weighing them. The average was taken from the three weights.

Figure 3.6. Flow table used to test the flow for each mixture.

For Phase I, a total of twenty-four mortar cubes were made per mixture. The mortar cubes were made by adding two lifts, where each lift was tamped a total of 32 times in four rounds. Rounds 1 and 3 followed one tamping path, while rounds 2 and 4 followed a different path. These two paths are shown in Figure 3.7. After both lifts were done, the top of the cube was smoothed by a trowel and put on a tray. When all twenty-four mortar cubes were made for that mixture, the tray was then placed in the curing chamber until it was time to demold and test the mortar cubes.

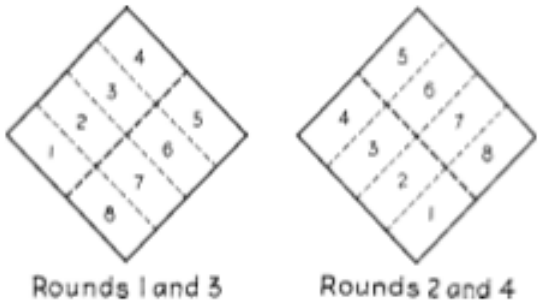


Figure 3.7. Order of tamping in cube molding of test specimens (ASTM Standard C109, 2016).

For Phase II, a total of twenty-four 2”x2”x2” mortar cubes per mixture were made using glasses S, T, V, and X at 20 and 30%. These cubes were made for compressive strength tests to help build off the information gathered from Phase I. Three 2”x2”x2” mortar cubes per sample were also used from Phase I and II to help gather information on the hardened air void and microscopy tests. The samples used for these two tests include the control, Class F fly ash, Q, S, and T with curing ages ranging between 197 days to 300 days.

3.3.2 Hardened Properties

3.3.2.1 Compressive Strength

ASTM C109 (2016) is the standard test method for compressive strength of hydraulic portland cement mortars using 2-in. [50mm] cube specimens. This standard provides details for the correct equipment, materials to use, mixture design quantities, how to mix and make samples, properly cure them, and run a compressive strength test. For this research, the mixture design quantity for twelve 2”x2”x2” cubes was doubled to make twenty-four 2”x2”x2” cubes.

The mortar cubes were demolded 24 hours after being placed in the curing chamber. The cubes not being tested went back into the curing chamber until their designated test date. On every break day, the unit weight and length and width measurements of each cube were taken prior to running a compressive strength test. The length and width measurements were performed with calipers by taking a measurement at the top, middle, and bottom of two different smooth sides on the cube. An average was then taken to get a

final length and width values. Measurements were only taken on the smooth surfaces of the cubes to ensure accurate measurements; the only rough surface of the cube was the spot not in the cube mold. These measurements made it possible to see if the samples were shrinking or expanding in the curing process and to turn the load value, pounds (lbs), given from the compressive strength machine into a unit of pressure, pounds per square inch (psi). Getting the weight and volume of each cube helped determine its density.

Compressive strength was measured following ASTM C109 (2016). Each test day has a time tolerance that must be followed to ensure accurate strength results for that mixture. For example, if some cubes need to be tested at 1 day, there is a ±30 minute from when the cubes were placed in the curing chamber the day before to perform the compressive strength test. As time goes on, the tolerance increases since most of the hydration has already occurred. Compressive strength tests were performed in a HUMBOLDT CM-3000-DIR compressive strength machine as seen in Figure 3.8.

Figure 3.8. HUMBOLDT CM-3000-DIR compressive strength machine used to test each sample.

The cubes were placed ontop of a black stand in the machine and were centered with the top plate and stand to ensure proper distribution of the load occurred. When applying a load onto the cubes, the machine load level was kept between 200-400 lbs/sec until the cube failed. The cubes were examined, documented, and properly disposed of after that mixture was done being tested. One cube per sample from the 7, 28, and 56 mixtures were saved and refrigerated to slow down hydration. They were saved just in case for future examination or testing.

3.3.2.2 Strength Activity Index (SAI)

ASTM C311 (2016) is the standard with test methods for sampling and testing fly ash or natural pozzolans for use in portland cement concrete. This ASTM is comprised of a wide variety of tests to determine various chemical and physical properties of a pozzolan sample. One test method used from this ASTM was the Strength Activity Index (SAI).

SAI involves making a portland cement control mixture and a test mixture with a 20% portland cement replacement. Six 2”x2”x2” cube samples are to be made and compressive strength ran on three cubes at 7 days and three cubes at 28 days. The strength results are then compared to the control sample. If the SAI for the test sample is 75% or greater at both 7 and 28 days, the test mixture passed the test.

In this research, a modified version of SAI was used. This version involved more test samples, two replacement levels, and more break days. The reason this test was modified was to help provide more data on how glass composition and replacement level play a significant role on compressive strength and durability. This modified version included making a portland cement mixture and test mixtures with a 20 and 30% portland cement replacement. These mixtures were tested at 1, 7, 28, 56, 90, and 182.5 days with three cubes per compressive break day.

3.3.3 Hardened Air-Void Analysis

ASTM C457 (2016) is the standard test method for microscopical determination of parameters of the air-void system in hardened concrete. Analysis of the hardened air-void structure can be performed with three different methods. These methods include Procedure A: linear transverse method, Procedure B: modified point-count method, and Procedure C: contrast enhanced method. For this research, Procedure C: the contrast enhanced method was used. This method was selected due to the availability of using a scanner along with the programs ImageJ and BubbleCounter to obtain all the air-void

information needed. ASTM C457 (2016) specifies that using a No.4 aggregate size, which was used in this research, involves an examined surface size of no less than 7 in^2. For this research, 3”x6” mortar cylinders were made, but unforeseen circumstances caused these cylinders to be disposed of. Due to time constraints and having extra cubes for each sample, three 2”x2”x2” mortar cubes from samples PC, FA2, Q, S, and T were taken to examine their air-void structure. Changing the surface size from 18in^2 to 4in^2 did not meet the 7in^2 requirement but running the air-void test was too important to ignore. The curing age of these cubes had PC at 300 days, FA2 at 299 days, Q at 289 days, and S and T at 197 days. Even with a max difference in curing time of 103 days, significant curing had already occurred to allow a comparison between air-void structures and microscopy results. It is widely accepted that portland cement mixtures containing pozzolans typically require 90 days of curing, compared to 28 days when no pozzolans are included, to obtain a high strength. All these samples were cured for significantly longer than 90 days.

Hardened air-void analysis is performed to get an idea of a mixture’s durability properties. To perform Procedure C, 2”x2”x2” mortar cubes were made with portland cement and 20% replacement level of Class F fly ash, sample Q, sample S, and sample T. This test was performed by taking the cubes out of the chamber at their respected curing age at that time, cutting them in half in the vertical direction, polishing the surface, coloring the cut surface with a black sharpie, pressing wollastonite powder into their pores, and scanning the sample using the scanner method procedure. Figure 3.9 shows the samples being prepared.

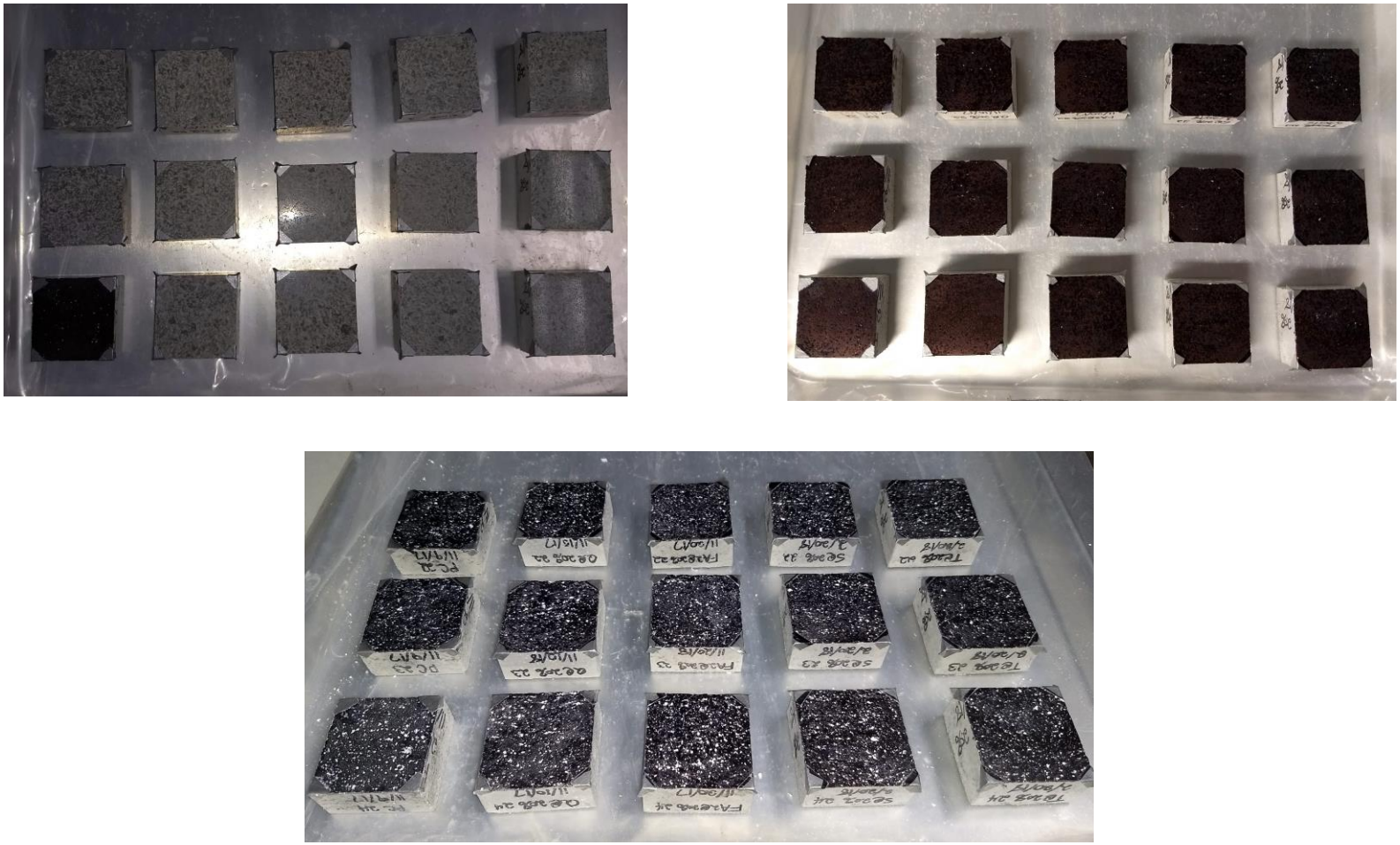


Figure 3.9. Half cut smoothed hardened air-void samples being prepared for scanning. Samples during the darkening process (top left). Samples after being darkened (top right). Darkened samples with wollastonite powder pressed into their pores (bottom).

The programs ImageJ and BubbleCounter were used to analyze each sample after each sample had been prepared. A white balance card was made to show the programs the differences in white and black intensities. The white powder and black sharpie closely resembled their corresponding color on the balance card, so the programs would produce accurate results. Duct tape was used to not only separate the white and black on the balance card but to also create padding on the four corners on the sample to protect the scanner's glass. Preparing the sample this way and including a balance card helped the programs correctly analyze each sample. Figure 3.10 shows what the samples looked like before and after getting them ready for this test. Each sample was scanned on an Epson Perfection V19 scanner.

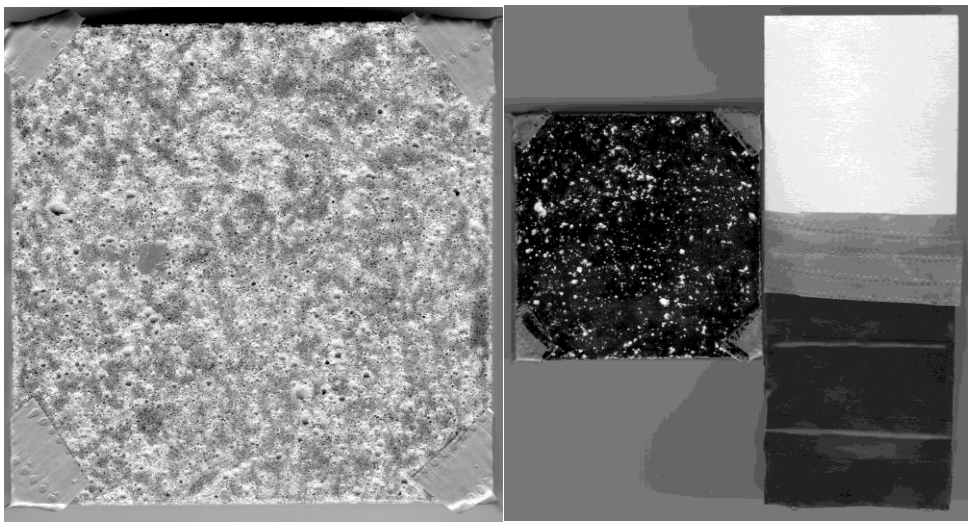


Figure 3.10. Example of a hardened air-void sample. (Left) Before samples were colored and wollastonite powder was pressed into the sample. (Right) After sample was prepared and scanned.

Every scanned sample was saved as a TIFF file. ImageJ and BubbleCounter analyze these TIFF files and provide results that inform the user on the sample's air-void and paste structure. The results from this test are discussed in Chapter 4.

3.3.4 Microstructural Characterization

A sample's microstructure plays a key role on how it will perform under stress, strain, and other environmental conditions. The formation of the microstructure during the curing process is essential to the strength and durability factors of concrete and mortar. To examine the microstructure and compositional variations of a specimen, secondary electron imaging (SEI), backscattered electron imaging (BSE), and energy-dispersive spectroscopy (EDS) were performed using a scanning electron microscope (SEM). SEI was performed on fractured surfaces, while BSE was performed on polished surfaces. EDS was used to examine the hardened sample's composition on BSE samples. The scanning electron microscope machine JEOL JSM-6490LV is shown in Figure 3.11.

Figure 3.11. JEOL JSM-6490LV microanalysis machine used to examine the microstructure of chosen samples using SEI, BSE, and EDS.

3.3.4.1 Secondary Electron Imaging (SEI)

Secondary electron imaging involves taking a fractured surface and evaluating the secondary electrons. Secondary electrons are low energy electrons that are generated near the surface of a sample and can provide a lot of information about the specimen's surface (Winter, 2012). SEI was performed at a magnification of 1000x the original size of the sample and with an acceleration voltage of 15kV.

3.3.4.2 Backscattered Electron Imaging (BSE) and Energy-Dispersive Spectroscopy (EDS)

Backscattered electron imaging (BSE) is performed on polished surfaces with primary electrons providing all the details. Primary electrons are more energetic than secondary electrons and are located throughout the sample and not just at the surface. For samples to show up on the SEM, the SEM's accelerating voltage should be increased to at least 15-20kV to excite the primary electrons. The amount of these electrons that will appear during testing are strongly dependent on the specimen's atomic number (Winter, 2012). BSE analysis was performed at a magnification of 1000x the original size of the sample with an accelerating voltage of 20kV. Backscattered electron imaging provides a cleaner surface for examining a sample's pore and phase structure. The flat, polished samples used for BSE are essential to ensure the data provided from running EDS is accurate.

Energy-Dispersive Spectroscopy (EDS) works in correlation with BSE. EDS takes the electrons within the specimen and can qualitatively and quantitatively provide the

composition and phases of the hardened sample. This is an important test to perform if someone wants to know what hydration phases and products have formed.

3.3.4.3 Preparing Samples for SEM Imaging

In this research, the portland cement and Class F fly ash, Q, S, and T samples at 20% replacement were used for microscopy examination. The portland cement and Class F fly ash samples were chosen so that the glass samples had a 100% portland cement mixture and a pozzolan mixture to compare to. Sample Q was selected due to its high compressive strength values. Samples S and T were selected due to them having very similar compositions but very different compressive strength values. All epoxy curing, air, and desiccator drying took place for a minimum of 16 hours. To prepare these samples for SEI, small pieces were taken from broken 2”x2”x2” mortar cubes and placed in a desiccator to ensure they were completely dry. The samples were then coated with 15nm of carbon in a vacuum chamber. Once coated, the samples were ready to be examined. Figure 3.12 through Figure 3.16 are examples of the samples during this process.

Figure 3.12. Epoxy (BSE) and non-epoxy (SEI) samples in the desiccator.

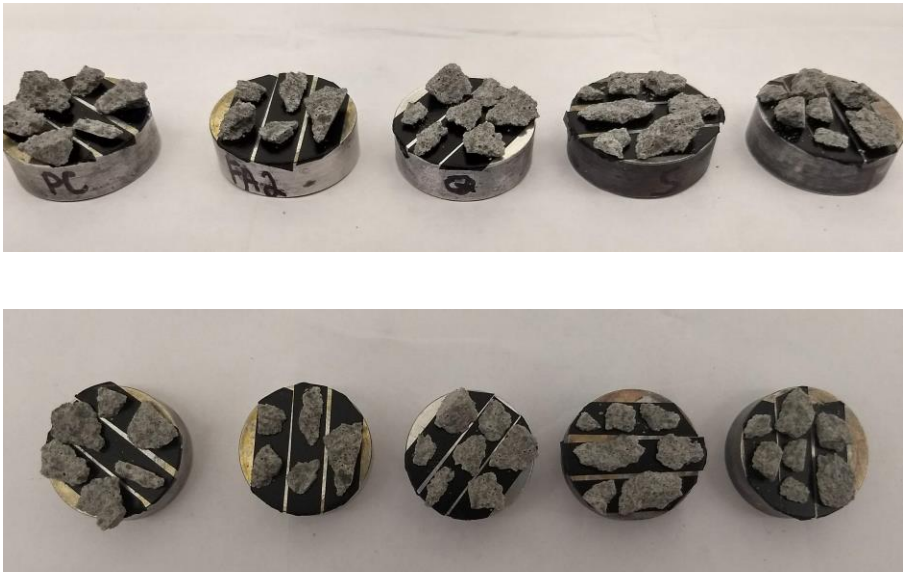


Figure 3.13. SEI samples prepared to be carbon coated.

Figure 3.14. LADD vacuum chamber for carbon coating.

Figure 3.15. SEI samples after being carbon coated.

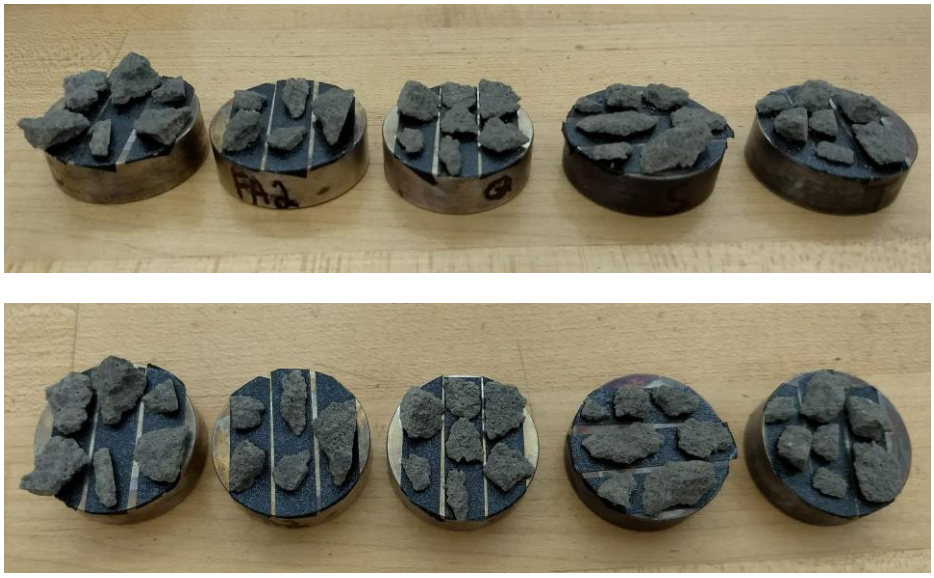


Figure 3.16. SEI samples after being carbon coated.

To prepare the samples for BSE, pieces were taken from 2”x2”x2” mortar cubes and were broken again to show a fresh, flat surface that had not been exposed to air for long. These pieces were then placed in a plastic mold and filled with epoxy. Once filled, they were placed in a vacuum for a few minutes to take out bubbles and force the epoxy into the sample. Each sample sat in their mold to cure before being taken out and polished. Once each sample was polished, they were air dried and placed in the desiccator, carbon coated, and examined. Figure 3.17 through Figure 3.22 show the samples through this process.

Figure 3.17. Chemicals to make epoxy along with the vacuum.

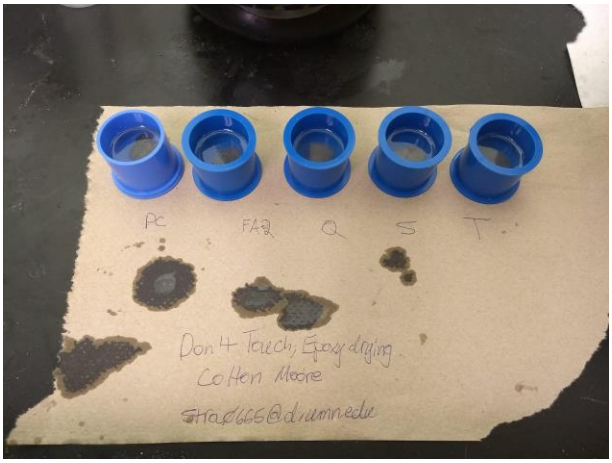


Figure 3.18. Epoxy samples curing in their plastic molds.

Figure 3.19. M-PREP 5 sample polisher setup (left) and sample being polished (right)

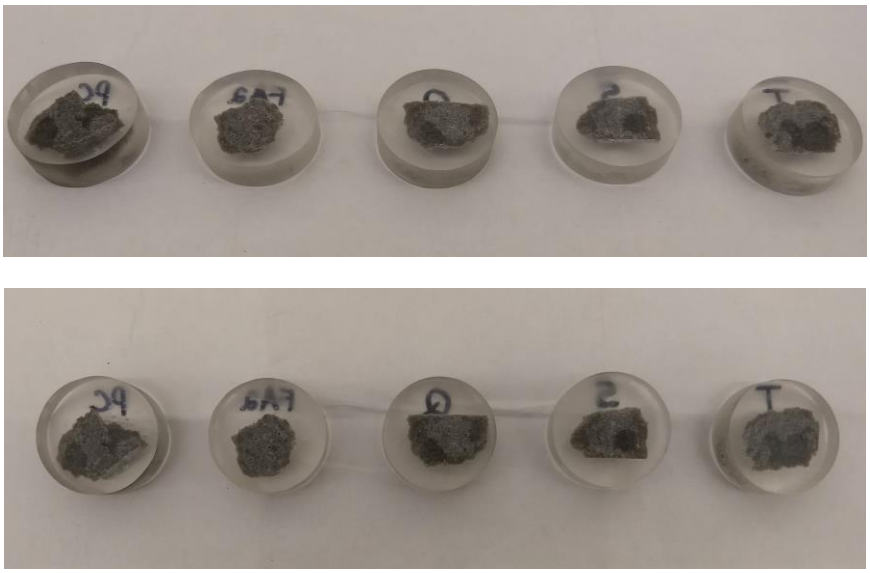


Figure 3.20. BSE samples before being carbon coated.

Figure 3.21. BSE samples before being carbon coated in LADD machine.

Figure 3.22. BSE samples after being carbon coated.

4 Results

This research was performed in two separate phases, each with their own question(s) to focus on. This chapter includes information on fresh and hardened properties for each phase along with results and discussions of the various tests performed. Fresh properties examined include flow, temperature, and unit weight. Hardened properties dealt with size, unit weight, compressive strength, hardened air-void analysis, and microscopy. The chemical composition helps get a better grasp as to why samples performed the way they did. For this research, specific compositional parameters were considered. These parameters were shown in Table 3.2. $Na_2O(eq)$ is the same as $Na_2O+0.658*K_2O$, which is the amount of alkalis in the sample.

4.1 Phase I

The first phase for this research dealt with taking fourteen out of the eighteen glasses and determining a correlation between compressive strength and composition. Only fourteen glasses were used in this research since the other four glasses, used in Phase II, were acquired later in the research. This correlation was investigated based on the need for understanding if all waste glass behaves the same in portland cement mixtures. Compressive strength was measured on 2”x2”x2” cubes at 1, 7, 28, 56, 90, and 182.5 days for the portland cement control and fourteen glasses and Class F fly ash samples at 20 and 30% replacement.

4.1.1 Mixture Design

Phase I mixing consisted of a portland cement control and fourteen waste glasses and Class F fly ash at 20 and 30% replacement. These replacements were selected based on the literature citing higher compressive strengths at 20% but a decreasing compressive strength greater than or equal to 30%. 2”x2”x2” cubes were made following the mixing procedure from ASTM C109 (2016). After the cubes were made, they were placed in a curing chamber for 24 hours waiting to be demolded. Once the cubes were demolded, they were placed back into the curing chamber until it was time to test them. Fresh and hardened properties where looked at during the mixing and curing process. The curing chamber saw a temperature and relative humidity of around 73°F and 95%, respectively.

4.1.2 Fresh Properties

The fourteen glass powder mixtures did not vary in appearance once all the materials were mixed together. The flow, water to cementitious material ratio (w/cm), temperature, and unit weight; however, varied between all the mixtures. This was expected since each glass powder varied in composition. Flow was measured to indicate how workable the mixture was. It was essential that the flow for all the samples was ± 5% of the control mixture. Table 4.1 and Table 4.2 show the fresh properties of all Phase I mixtures at 20 and 30% replacements. The flow value is a calculated percent, while temperature and unit weight are averages. The temperature was taken before the cube molds were filled, and the unit weight was measured after the molds were filled.

Table 4.1. Phase I fresh properties for 20% replacement.

Sample	w/cm Ratio	Flow (%)	Temperature (°F)	Unit Weight (lbf/in^3)	Weight (g)	Weight (lbs)	Cube Volume (in^3)
Control PC	0.485	38.61	70.6	0.0765	277.5	0.6118	8
A	0.474	41.82	69.6	0.0749	271.8	0.5993	8
B	0.465	37.78	69.5	0.0747	271.0	0.5975	8
C	0.476	40.23	69.4	0.0745	270.3	0.5960	8
D	0.475	43.26	69.5	0.0733	265.8	0.5861	8
E	0.462	43.26	69.2	0.0745	270.3	0.5960	8
G	0.446	34.77	68.9	0.0726	263.5	0.5809	8
H	0.474	36.98	69.1	0.0752	273.0	0.6019	8
J	0.472	40.58	70.5	0.0752	273.0	0.6019	8
K	0.467	39.24	69.3	0.0755	274.0	0.6041	8
L	0.472	42.26	69.4	0.0752	273.0	0.6019	8
M	0.450	34.88	68.9	0.0736	267.0	0.5886	8
P	0.475	41.76	68.6	0.0753	273.3	0.6026	8
Q	0.475	38.13	68.9	0.0755	274.0	0.6041	8
R	0.476	35.64	69.9	0.0759	275.5	0.6074	8
Class F Fly Ash	0.439	36.88	69.9	0.0762	276.3	0.6092	8

Table 4.2. Phase I fresh properties for 30% replacement

Sample	w/cm Ratio	Flow (%)	Temperature (°F)	Unit Weight (lbf/in^3)	Weight (g)	Weight (lbs)	Cube Volume (in^3)
Control PC	0.485	38.61	70.6	0.0765	277.5	0.6118	8
A	0.473	37.01	68.8	0.0744	270.0	0.5952	8
B	0.460	37.41	69.9	0.0745	270.2	0.5956	8
C	0.476	38.98	69.0	0.0735	266.8	0.5883	8
D	0.473	43.20	68.3	0.0738	267.8	0.5905	8
E	0.465	37.78	68.4	0.0735	266.7	0.5879	8
G	0.446	35.04	68.7	0.0726	263.3	0.5805	8
H	0.474	35.53	69.1	0.0747	271.0	0.5975	8
J	0.469	41.79	69.0	0.0751	272.5	0.6008	8
K	0.465	36.73	69.4	0.0756	274.2	0.6044	8
L	0.467	41.24	69.4	0.0749	271.8	0.5993	8
M	0.455	36.26	69.3	0.0727	263.7	0.5813	8
P	0.473	38.64	68.3	0.0754	273.7	0.6033	8
Q	0.473	41.44	68.3	0.0752	273.0	0.6019	8
R	0.482	38.82	69.5	0.0750	272.2	0.6000	8
Class F Fly Ash	0.429	42.21	69.0	0.0756	274.2	0.6044	8

The samples containing glass at both replacement levels weighed less, had lower temperatures, and required less water when compared to the portland cement sample. The temperature difference is likely due to the presence of the pozzolans reducing the portland cement, meaning more of the reaction will happen at a later date. A lower w/cm ratio correlates to why the flow percentage would be less. The w/cm ratio for the glass samples ranged from 0.446 to 0.482, which caused the flow to range from 35.04% to 43.20%. For the most part, as the replacement level of glass increased, the w/cm ratio decreased. As stated in 2.5.1.1, this could be due to the glasses' particle size, high specific surface area, the glassy surface on the glass particles, or the low absorption level that glass powder has.

4.2 Phase II

The second phase for this research dealt with taking the remaining four glass mixtures and measuring their compressive strength at 1, 7, 28, 56, 90, and 182.5. These results were then compared with Phase I results to help increase the correlation between compressive strength and composition. This phase also included taking five samples, portland cement, Class F fly ash, and three glasses, and performing hardened air-void analysis and microstructural characterization to further examine how these samples formed in relation to each other. The three glass samples selected were Q, S, and T. They were selected due to the Q samples being the strongest of all the glass samples, S being a weak soda-lime container glass, and T being a strong soda-lime container glass. S and T were also chosen because they had very similar compositions, yet different compressive strength results. Part of this could be due to S and T being from different parts of the MRF cleaning process; S is clean, and T is dirty. The fly ash and glass samples used for air-void and microscopy were made using a 20% replacement of portland cement due to this replacement outperforming the 30% replacement. The curing age of these cubes included the portland cement control at 300 days, FA2 at 299 days, Q at 289 days, and S and T at 197 days.

4.2.1 Mixture Design

Phase II mixing used glasses S, T, V, and X. The mixing procedure was the same as it was for Phase I.

4.2.2 Fresh Properties

The four glass mixtures didn't vary in appearance once all the materials were mixed together. The flow, water to cementitious material ratio (w/cm), temperature, and unit weight; however, changed between all the mixtures. This was expected since each glass powder varied in composition and somewhat in particle size distribution. Flow was measured to indicate how workable the mixture was. The methodology for the Strength Activity Index (SAI) requires that the flow for all the samples were ± 5% of the control mixture. Table 4.3 and Table 4.4 show the fresh properties of all Phase II cube mixtures. These tables show the variations between each mixture at 20 and 30% replacements. The flow value is a calculated percent and temperature and unit weight are averages. The temperature was taken before the cube molds were filled, while the weight was measured after the molds were filled.

Table 4.3. Phase II cube fresh properties for 20% replacement

Sample	w/cm Ratio	Flow (%)	Temperature (°F)	Unit Weight (lbf/in^3)	Weight (g)	Weight (lbs)	Cube Volume (in^3)
S	0.458	37.91	68.4	0.0748	271.3	0.5982	8
T	0.462	36.90	69.3	0.0760	275.8	0.6081	8
V	0.458	39.39	68.3	0.0766	278.0	0.6129	8
X	0.448	41.04	68.1	0.0747	271.2	0.5978	8

Table 4.4. Phase II cube fresh properties for 30% replacement

Sample	w/cm Ratio	Flow (%)	Temperature (°F)	Unit Weight (lbf/in^3)	Weight (g)	Weight (lbs)	Cube Volume (in^3)
S	0.455	36.29	69.1	0.0743	269.5	0.5941	8
T	0.462	40.48	68.6	0.0750	272.2	0.6000	8
V	0.458	38.44	67.8	0.0757	274.8	0.6059	8
X	0.441	39.38	68.0	0.0739	268.0	0.5908	8

Just as in Phase I, the pozzolan samples at each replacement level weighed less, had lower temperature, and required less water when compared to the portland cement mixture. The w/cm ratio for the glass samples ranged from 0.441 to 0.462, which caused the flow to range from 36.29% to 40.48%.

4.3 Phase I and Phase II Results

4.3.1 General Comments

Compressive strength and strength activity index (SAI) go hand in hand. The only significant difference between the two is how they get reported. Compressive strength reports the results in psi and indicates how that sample's strength did on that break day. SAI reports the results in a percentage and indicates how that sample's strength did in comparison to the control sample's strength. The control sample will always have a SAI of 100%, regardless of how its compressive strength was. Samples that have a SAI less than 100% indicate that they had a weaker compressive strength than the control sample on that break day. Samples with a SAI greater than or equal to 100% indicate that they had a compressive strength equal to or greater than the control sample on that break day.

From ASTM C618 (2015), a SAI of 75% at 7 and 28 days is required for a mixture design with a pozzolan to pass. Comparing between 20 and 30% portland cement replacements, samples with 20% replacement performed better than the 30% replacement. By examining the 20% replacement, sample Q was the strongest and sample S was the weakest at 28 days. For 56 days, sample R was the strongest and sample S was the weakest. For 90 days, sample Q was the strongest and sample S was the weakest.

In total, thirteen glass mixtures with a 20% replacement passed the SAI requirement at 7 and 28 days, while only two glass mixtures with a 30% replacement passed. It was taken into consideration that the SAI should be 75% or greater on every test day, even after 28 days, to ensure the glass sample would continue to have a strong enough compressive strength at later curing ages. This is due to the continuous formation of hydration phases and products in pozzolanic reactions through 90 days of curing. Some samples with a 20% replacement had unforeseen strength drops. This caused these samples to have a less than acceptable SAI on one break day but would then come back into acceptable range on the next break day. Samples D, H, and S had this strange phenomenon occur to them. There was also a strength drop for sample J at 6 months, but it was determined to be an issue with the testing machine and not the sample.

An explanation for these strength drops could lie within their microstructure at the time. Issues that could cause these drops include a sample having a significant amount of large entrapped air voids, contaminants, or poor development of hydration phases and

products. Entrapped air voids are not only a result of mixing but can also come from how the phases are forming within the sample. The amount of CH within a sample is important to note throughout the curing process. CH can help the strength of a sample by filling entrapped air voids and causing the sample to be considered solid, but it can significantly decrease the sample's strength the moment it reacts with water; CH is very reactive to water. Water will dissolve any CH encountered and cause more pores to be empty resulting in a weak sample (Thomas and Jennings, 2018). While breaking samples D, H, and S, it was noted that the inside of the all these cubes seemed porous and had dark spots around the time when they had the strength drop. Examples of these samples are shown in Figure 4.1 through Figure 4.4. Things to note in these pictures are any dark or semi dark gray spots. Those areas possibly indicate unhydrated portland cement balls. On cube H at 20% replacement, small white pieces were observed. This could be due to parts of the mixture not being fully hydrated or mixed properly. Circles have been added to each picture to provide examples of what to look for.

Figure 4.1. Example of H at 20% at 28 days with white and dark spots.

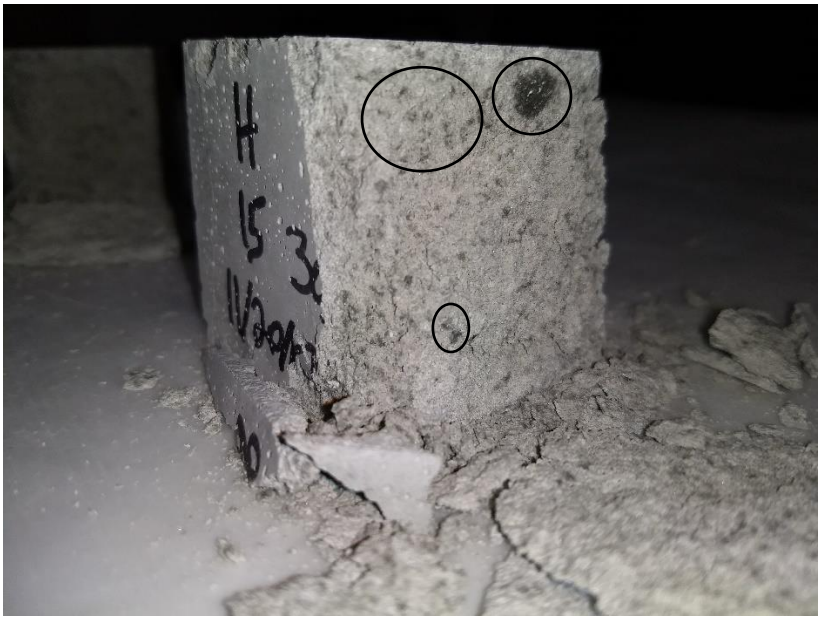


Figure 4.2. Example of H at 30% at 90 days with dark spots.

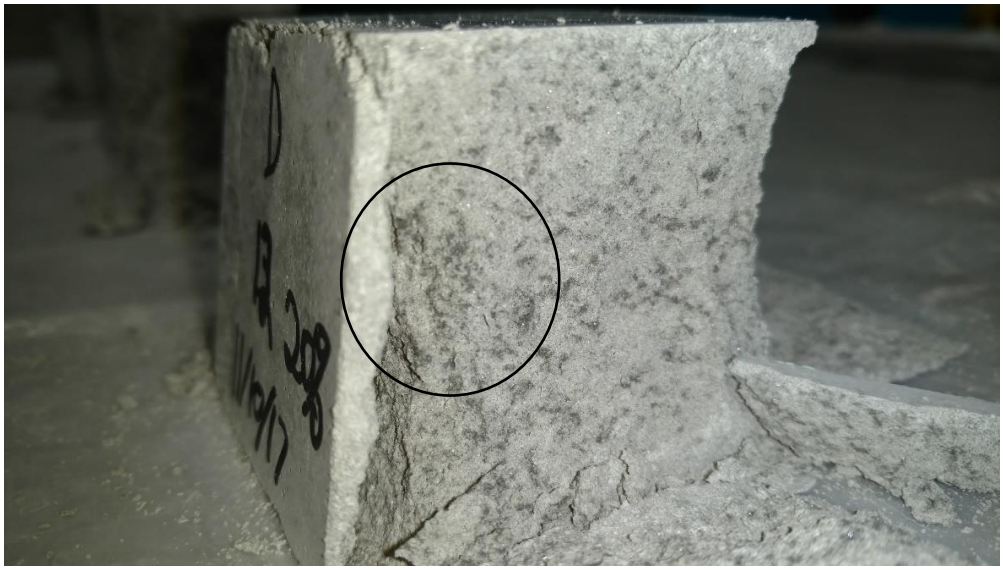


Figure 4.3. Example of D at 20% at 56 days with dark spots.

Figure 4.4. Examples of S at 20% at 56 days with dark spots.

Using glass powder as a pozzolan has been controversial due to studies noticing that their samples have had a low early strength, but a high later strength or high early and later

strengths (Du and Hwee Tan, 2015; Kamali and Ghahremaninezhad, 2016; Shi and Zheng, 2007). This can be a problem if a project needs a high compressive strength by an early date. Results further discussing early and later strengths can be found in the next few sections. Overall, SAI and compressive strength results from 1 day to 6 months for all 20 and 30% replacement samples can be found in Figure 4.5 and Figure 4.6, respectively. The main perspective to take from these two figures is the range the data spans.

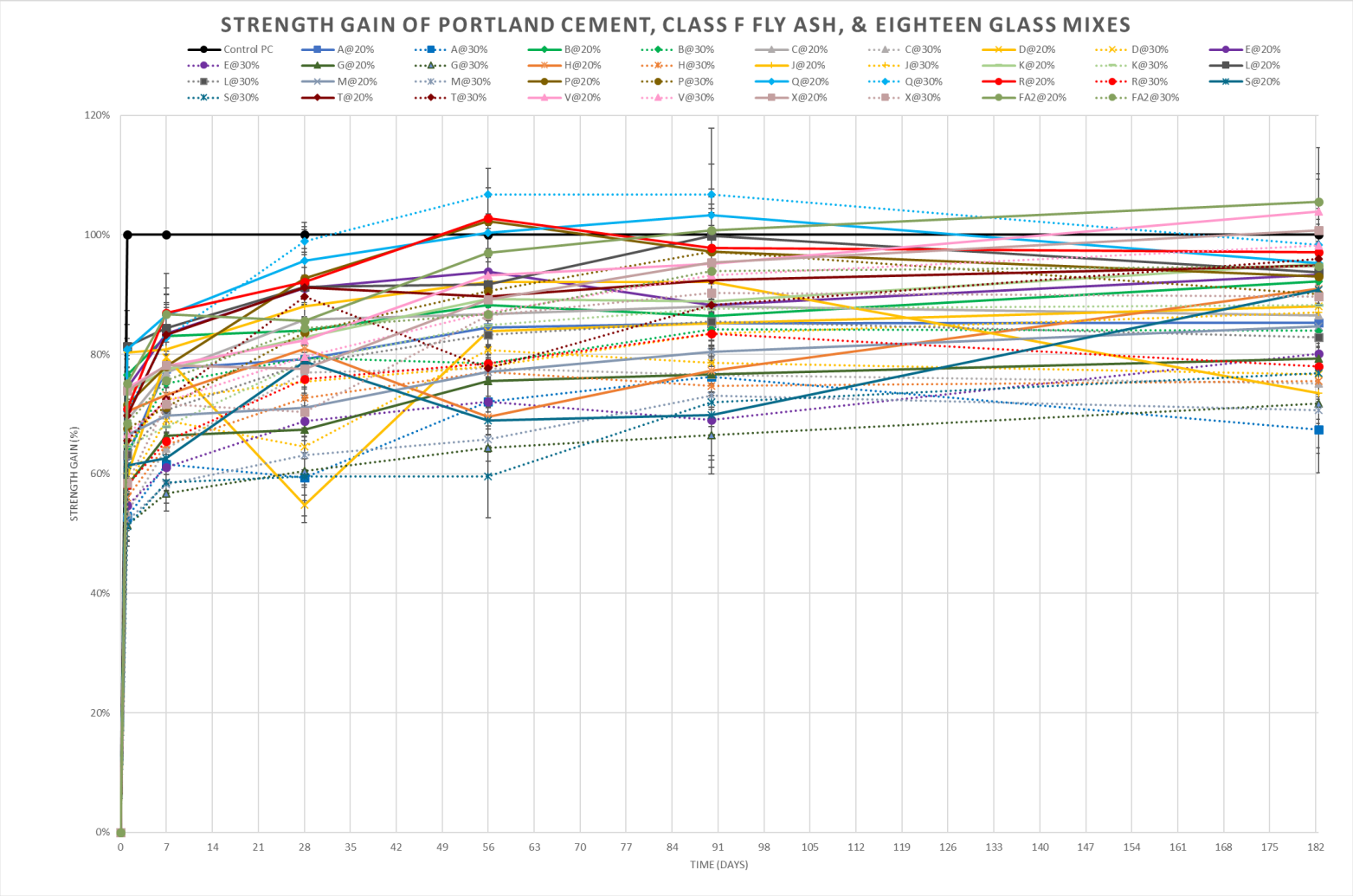


Figure 4.5. SAI of all samples from 1 day to 6 months.

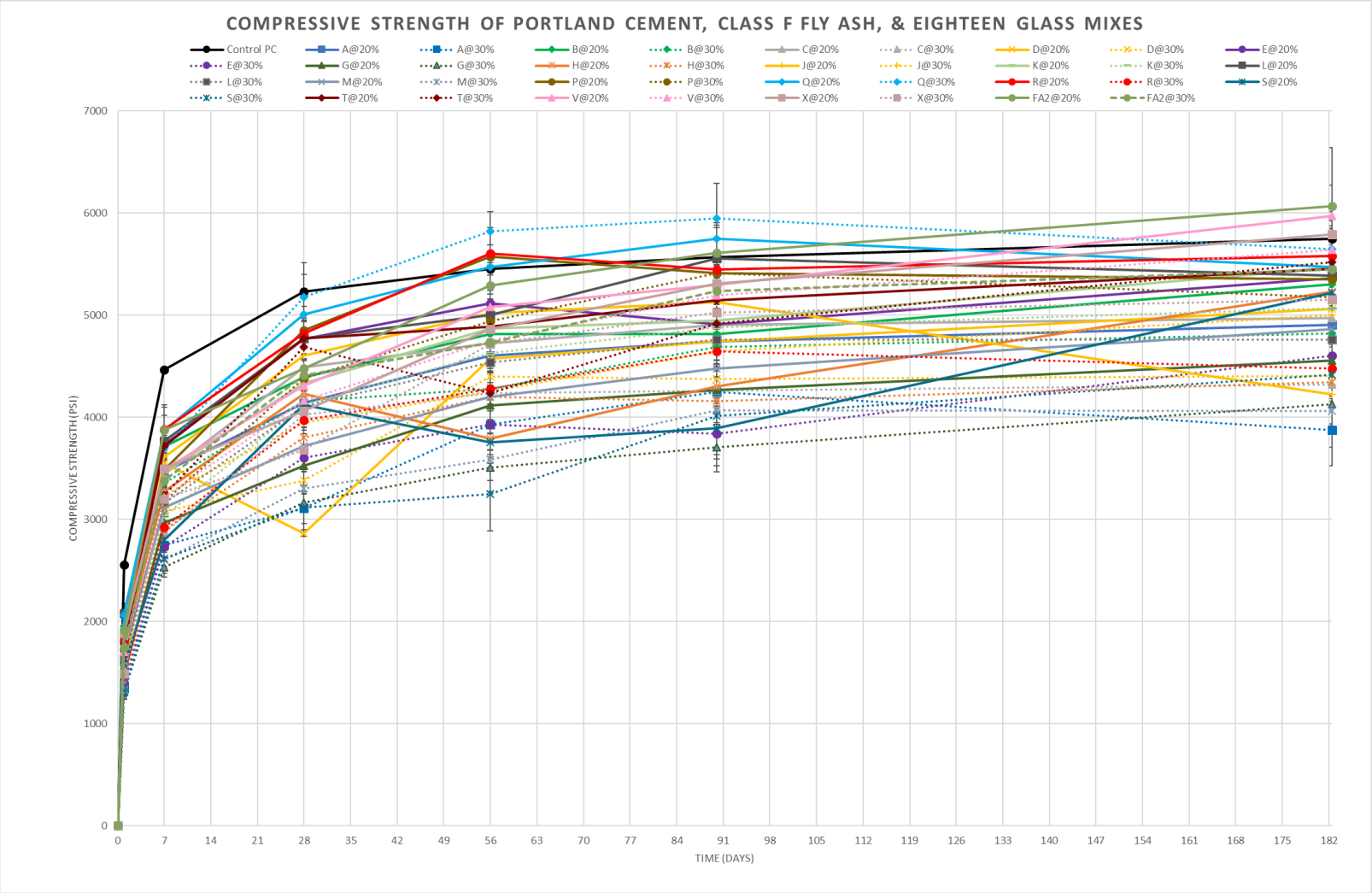


Figure 4.6. Compressive strength of all samples from 1 day to 6 months.

4.3.2 Replacement Level

One of the main purposes for this research was further expanding on glass compositions using two common portland cement replacement levels, 20 and 30%, found in the literature. These two replacement levels have provided useful data that can help build off the knowledge known on using glass powder as a pozzolan.

4.3.2.1 Comments on 20% Replacement Level Results

Between the two portland cement replacements examined, 20% performed the best. Three out of the eighteen glass samples at 28 days had a SAI under 75%. The three samples that failed were D, G, and M. The number of samples not meeting the SAI requirement decreased with each break day. Excluding the sample J at 6 months, due to equipment issues discussed earlier, only one sample after 28 days had a SAI under 75%; this failure occurred at 56 days for sample S. Figure 4.7 shows the compressive strength range between all the samples, while Table 4.5 and Table 4.6 show the numerical compressive strength and SAI values for the samples.

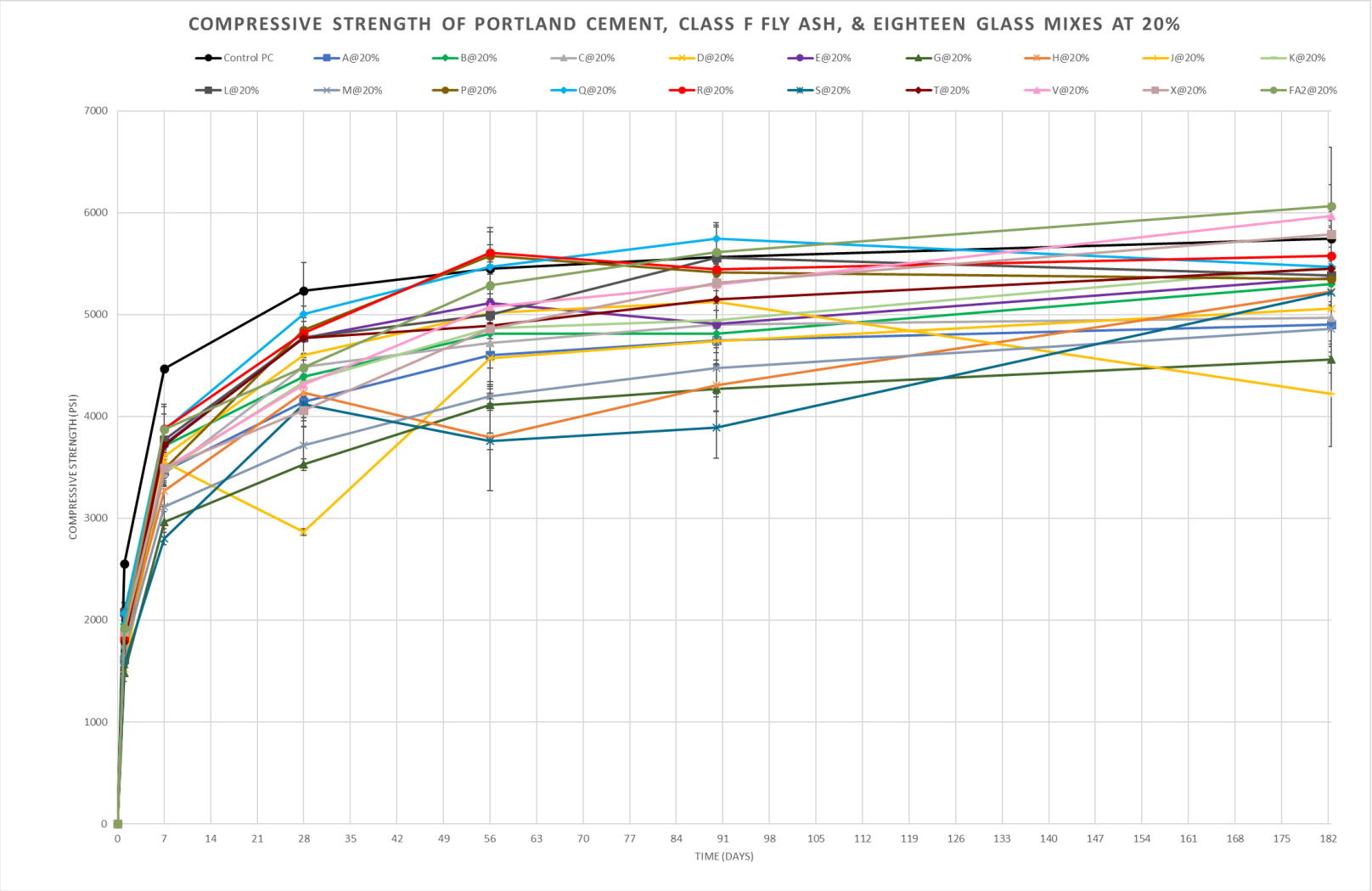


Figure 4.7. Compressive strength of all samples at 20% replacement from 1 day to 6 months.

Table 4.5. Compressive strength results up to 6 months at 20% replacement.

Sample	w/cm 20%	20% Compressive Strength 1 Day (psi)	20% Compressive Strength 7 Days (psi)	20% Compressive Strength 28 Days (psi)	20% Compressive Strength 56 Days (psi)	20% Compressive Strength 90 Days (psi)	20% Compressive Strength 6 Months (psi)
PC	0.485	2553	4466	5231	5450	5567	5745
A	0.474	1613	3463	4142	4604	4743	4903
B	0.465	1955	3709	4391	4811	4812	5299
C	0.476	1761	3439	4486	4724	4904	4969
D	0.475	1522	3552	2865	4572	4741	5059
E	0.462	1899	3729	4767	5115	4911	5360
G	0.446	1481	2964	3528	4115	4268	4556
H	0.474	1799	3269	4232	3792	4304	5227
J	0.472	2049	3610	4603	5020	5126	4221
K	0.467	1880	3461	4334	4867	4946	5466
L	0.472	2077	3769	4774	4998	5556	5385
M	0.450	1696	3113	3717	4198	4474	4863
P	0.475	1827	3482	4849	5575	5413	5347
Q	0.475	2063	3866	5005	5471	5748	5470
R	0.476	1809	3880	4819	5605	5444	5579
S	0.458	1567	2799	4122	3756	3890	5218
T	0.462	1781	3718	4773	4888	5147	5450
V	0.458	1900	3486	4310	5079	5296	5968
X	0.448	1886	3494	4060	4860	5310	5789
Class F Fly Ash	0.439	1918	3874	4478	5287	5611	6063

Table 4.6. SAI results up to 6 months at 20% replacement.

Sample	w/cm 20%	20% Strength Gain 1 Day (%)	20% Strength Gain 7 Days (%)	20% Strength Gain 28 Days (%)	20% Strength Gain 56 Days (%)	20% Strength Gain 90 Days (%)	20% Strength Gain 6 Months (%)
PC	0.485	100	100	100	100	100	100
A	0.474	63	78	79	84	85	85
B	0.465	77	83	84	88	86	92
C	0.476	69	77	86	87	88	86
D	0.475	60	80	55	84	85	88
E	0.462	74	83	91	94	88	93
G	0.446	58	66	67	76	77	79
H	0.474	70	73	81	70	77	91
J	0.472	80	81	88	92	92	73
K	0.467	74	78	83	89	89	95
L	0.472	81	84	91	92	100	94
M	0.450	66	70	71	77	80	85
P	0.475	72	78	93	102	97	93
Q	0.475	81	87	96	100	103	95
R	0.476	71	87	92	103	98	97
S	0.458	61	63	79	69	70	91
T	0.462	70	83	91	90	92	95
V	0.458	74	78	82	93	95	104
X	0.448	74	78	78	89	95	101
Class F Fly Ash	0.439	75	87	86	97	101	106

4.3.2.2 Comments on 30% Replacement Level Results

The mixtures containing 30% portland cement replacement level did not perform as well as those with a 20% replacement level. Eight out of the eighteen glass samples at 28 days had a SAI under 75%. The eight samples that failed were A, D, E, G, H, M, S, and X. The number of samples not meeting the SAI requirement decreased with each break day. The amount that failed dropped to five samples at 56 and 90 days and ended at two samples at 6 months. For the most part, the amount passing with a SAI of 75%, besides sample Q, are less than the 20% replacement. Figure 4.8 shows the compressive strength range between all the samples, while Table 4.7 and Table 4.8 show the numerical compressive strength and SAI values for the samples.

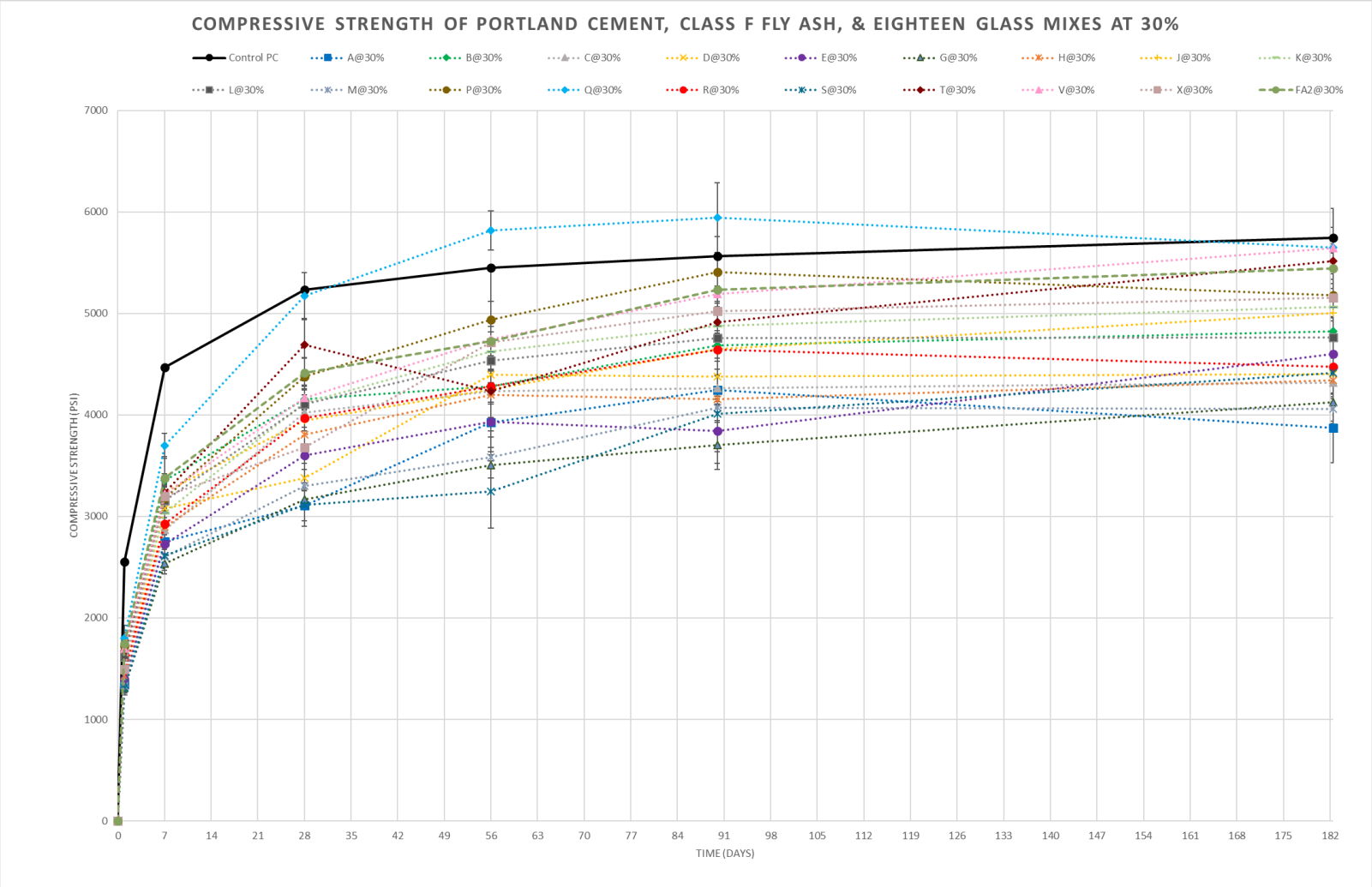


Figure 4.8. Compressive strength of all samples for 30% replacement from 1 day to 6 months.

Table 4.7. Compressive strength results up to 6 months at 30% replacement

Sample	w/cm 30%	30% Compressive Strength 1 Day (psi)	30% Compressive Strength 7 Days (psi)	30% Compressive Strength 28 Days (psi)	30% Compressive Strength 56 Days (psi)	30% Compressive Strength 90 Days (psi)	30% Compressive Strength 6 Months (psi)
PC	0.485	2553	4466	5231	5450	5567	5745
A	0.473	1346	2751	3107	3928	4246	3872
B	0.460	1621	3354	4155	4280	4685	4822
C	0.476	1368	2869	4024	4235	4261	4318
D	0.473	1481	3077	3377	4398	4377	4402
E	0.465	1396	2729	3603	3930	3840	4604
G	0.446	1312	2533	3166	3507	3704	4126
H	0.474	1429	2896	3804	4198	4158	4342
J	0.469	1657	3238	3946	4252	4648	5003
K	0.465	1651	3033	4121	4624	4879	5068
L	0.467	1615	3157	4106	4536	4760	4762
M	0.455	1330	2602	3302	3586	4070	4059
P	0.473	1725	3178	4379	4939	5411	5177
Q	0.473	1799	3696	5177	5817	5946	5647
R	0.482	1482	2925	3969	4280	4646	4478
S	0.455	1308	2614	3117	3248	4010	4414
T	0.462	1673	3236	4690	4234	4916	5516
V	0.458	1701	3220	4165	4745	5193	5640
X	0.441	1491	3201	3682	4717	5025	5153
Class F Fly Ash	0.429	1746	3378	4413	4729	5233	5445

Table 4.8. SAI results up to 6 months at 30% replacement

Sample	w/cm 30%	30% Strength Gain 1 Day (%)	30% Strength Gain 7 Days (%)	30% Strength Gain 28 Days (%)	30% Strength Gain 56 Days (%)	30% Strength Gain 90 Days (%)	30% Strength Gain 6 Months (%)
PC	0.485	100	100	100	100	100	100
A	0.473	53	62	59	72	76	67
B	0.460	64	75	79	79	84	84
C	0.476	54	64	77	78	77	75
D	0.473	58	69	65	81	79	77
E	0.465	55	61	69	72	69	80
G	0.446	51	57	61	64	67	72
H	0.474	56	65	73	77	75	76
J	0.469	65	73	75	78	83	87
K	0.465	65	68	79	85	88	88
L	0.467	63	71	79	83	86	83
M	0.455	52	58	63	66	73	71
P	0.473	68	71	84	91	97	90
Q	0.473	70	83	99	107	107	98
R	0.482	58	66	76	79	83	78
S	0.455	51	59	60	60	72	77
T	0.462	66	72	90	78	88	96
V	0.458	67	72	80	87	93	98
X	0.441	58	72	70	87	90	90
Class F Fly Ash	0.429	68	76	84.36	86.76	94	95

4.3.2.3 20% vs. 30% Replacement Level

Comparing these two portland cement replacement levels indicate that the 20% replacement outperformed the 30% replacement in compressive strength. A 20% replacement level had more samples meeting the SAI requirements from the start than the 30% replacement level. Sample Q was the only sample that regularly had higher strength values at a 30% replacement.

4.3.3 Effects of Composition and Mixing Parameters to Compressive Strength

The other large part of this research examined how the compositions of each glass powder effected compressive strength over multiple test days. This is essential to examine since no literature has been found utilizing many types of glasses with various compositions. Each type of glass can be classified into a type and waste stream based on what their compositions were. The glass types found from the eighteen glasses are nine soda-lime container, two soda-lime container and plate, three soda-lime plate, one aluminosilicate glass & glass ceramic, one TV/CRT panel (barium) & soda-lime container, one phosphate & soda-lime container, and one E-Glass. There was not a specific guide used to indicated what each glass used classified as. Instead, several texts on glass were used to help classify these glasses and provide a more unified table to help classify future glasses. These texts are shown in Table 2.3 in Section 2.4.3.

As stated before, a mixture design containing a pozzolan just needs a SAI of 75% to be considered a pozzolan with a high enough compressive strength at that break day. E-Glass, sample Q, performed the best out of all the glasses. This was expected since E-Glass has a substantial amount of CaO in its composition to replace the CaO lost from using less portland cement. The average compressive strength for each break day was taken to help provide a better comparison between all the samples. This was because this research was comprised of a wide variety of glass types with more than one sample type making it up.

Soda-lime container glass is an important glass type to examine since it is the most common type of glass used on the planet. By looking at each soda-lime container glass individually, it was observed that a few of them do not pass the SAI requirement at 7 and 28 days as shown in Figure 4.9 and Figure 4.11. By taking the average of all the soda-lime container glasses for 20%, the SAI requirement of 75% passes from 7 days and beyond. Using the average for each glass type helps provide a better way to compare each type to one another. These averages are shown in Figure 4.7 and Figure 4.9. This goes to show that not one glass or even two of the same glass types are the same. Composition, curing, replacement level, and properties of each glass can be key contributors to how they will perform during various tests. Figure 4.9 and Figure 4.11 show how there is a variation between each glass type and a variation within the same glass type when compared to SAI for 20 and 30%, respectively. Figure 4.10 and Figure 4.12 take the average SAI of each glass type to provide an easier way to examine how they did at 20 and 30% replacement, respectively.

Table 4.9 and Table 4.10 show the average SAI from 1 day to 6 months for 20 and 30% replacement levels, respectively. These two tables help provide a numerical value for what is shown in the previous figures and also show a visual for what day(s) a glass type failed.

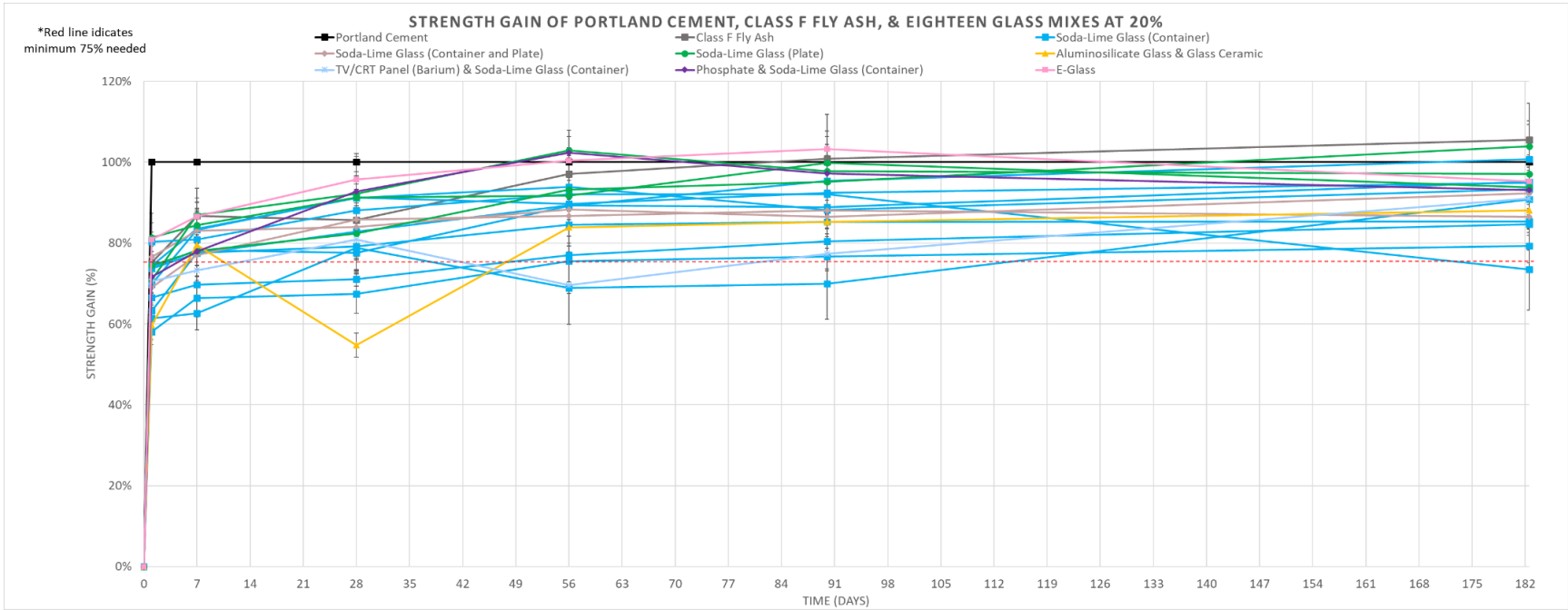


Figure 4.9. SAI showing variations in results comparing control samples and glass classifications at 20% replacement.

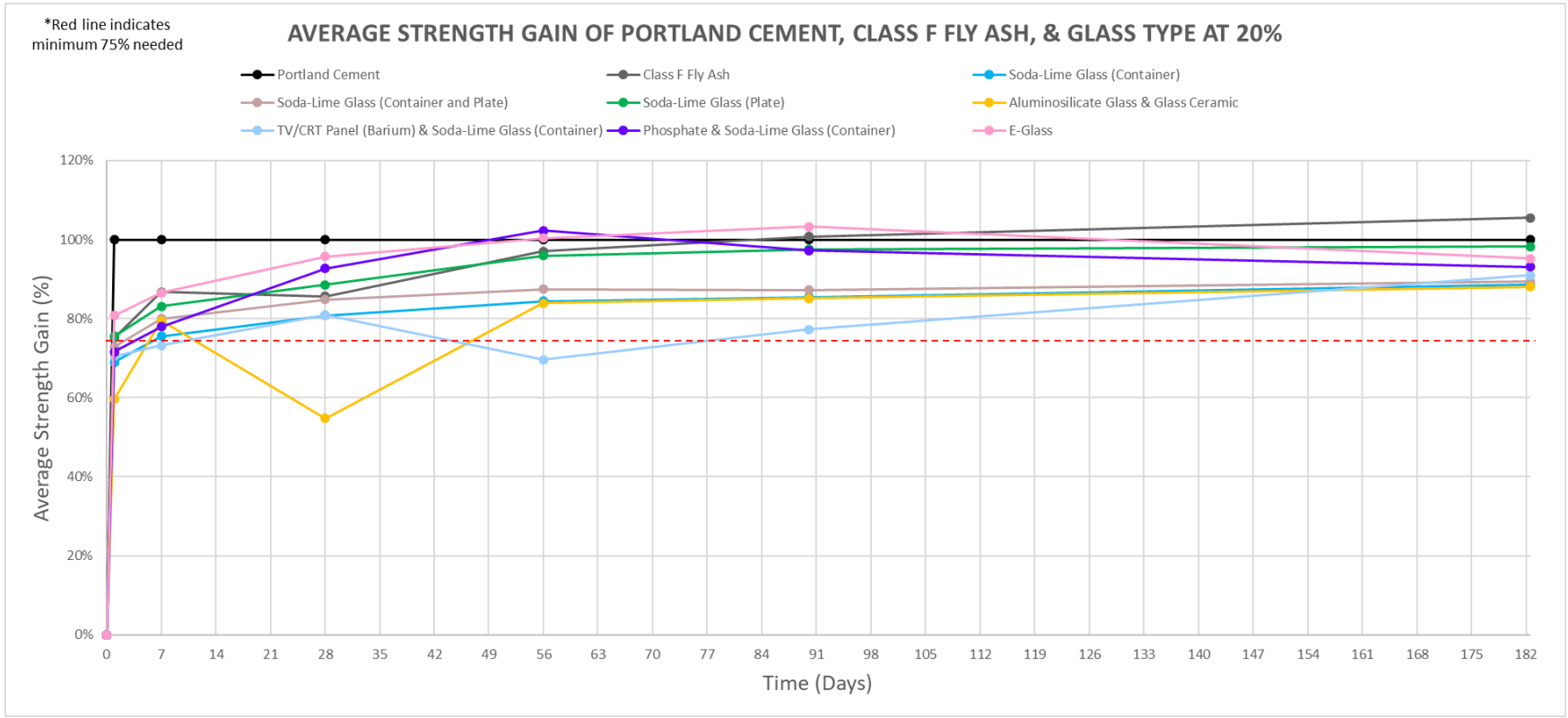


Figure 4.10. Average SAI results comparing control samples and glass classifications at 20% replacement.

Table 4.9. Average SAI at 20% of glass types and control samples from 1 day to 6 months.

*Red indicates that sample type did not meet 75% SAI minimum	**Average 20% SAI at 1 day (%)**	**Average 20% SAI at 7 days (%)**	**Average 20% SAI at 28 days (%)**	**Average 20% SAI at 56 days (%)**	**Average 20% SAI at 90 days (%)**	**Average 20% SAI at 6 months (%)**
Soda-Lime Glass (Container)	69	76	81	84	85	89
Soda-Lime Glass (Container and Plate)	73	80	85	87	87	89
Soda-Lime Glass (Plate)	76	83	89	96	98	98
Aluminosilicate Glass & Glass Ceramic	60	80	55	84	85	88
TV/CRT Panel (Barium) & Soda-Lime Glass (Container)	70	73	81	70	77	91
Phosphate & Soda-Lime Glass (Container)	72	78	93	102	97	93
E-Glass	81	87	96	100	103	95
Portland Cement	100	100	100	100	100	100
Class F Fly Ash	75	87	86	97	101	106

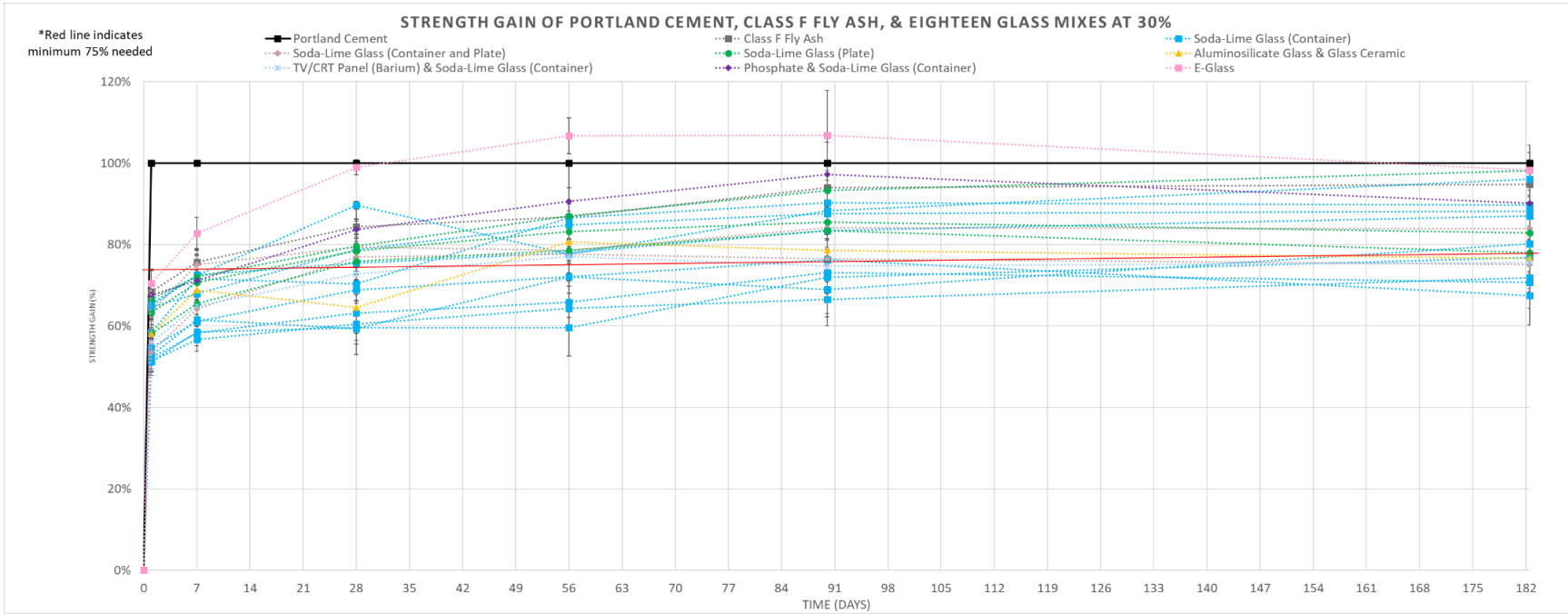


Figure 4.11. SAI showing variation in results comparing control samples and glass classifications at 30% replacement.

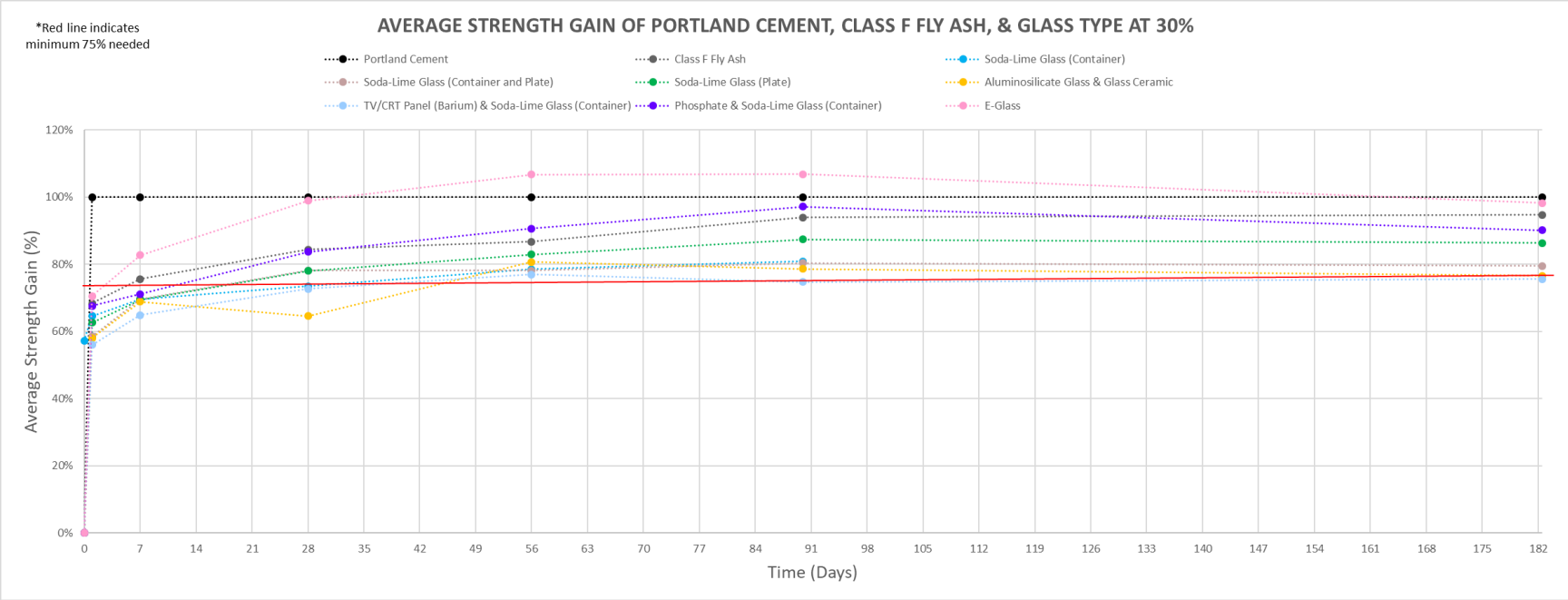


Figure 4.12. Average SAI results comparing control samples to glass classifications at 30% replacement.

Table 4.10. Average SAI at 30% of glass types and control samples from 1 day to 6 months.

*Red indicates that sample type did not meet 75% SAI minimum	**Average 30% SAI at 1 day (%)**	**Average 30% SAI at 7 days (%)**	**Average 30% SAI at 28 days (%)**	**Average 30% SAI at 56 days (%)**	**Average 30% SAI at 90 days (%)**	**Average 30% SAI at 6 months (%)**
Soda-Lime Glass (Container)	57	65	70	73	79	81
Soda-Lime Glass (Container and Plate)	59	70	78	78	80	80
Soda-Lime Glass (Plate)	63	69	78	83	87	86
Aluminosilicate Glass & Glass Ceramic	58	69	65	81	79	77
TV/CRT Panel (Barium) & Soda-Lime Glass (Container)	56	65	73	77	75	76
Phosphate & Soda-Lime Glass (Container)	68	71	84	91	97	90
E-Glass	70	83	99	107	107	98
Portland Cement	100	100	100	100	100	100
Class F Fly Ash	68	76	84	87	94	95

One important thing to note while examining this data, especially the average data, is the amount of glass samples per glass type. As discussed earlier in this section, soda-lime container glass had nine different glass samples forming that type, while phosphate & soda-lime container glass or E-Glass only had one glass sample forming those types.

By looking at the averages from Table 4.9 and Table 4.10, E-Glass, for the most part, was the strongest glass type out of the seven classified types for both 20 and 30% replacement levels. For 20% replacement level, the following two strongest glass types after E-Glass were soda-lime plate and phosphate and soda-lime container glasses. If these two were not the strongest for a break day, they were close together for the second strongest. Out of the seven different glass types examined, soda-lime container glass was either the fifth or sixth strongest glass type. For 30% replacement level, the strongest glass type after E-Glass was phosphate & soda-lime container glass followed by soda-lime plate glass. Soda-lime plate glass was not as close to the phosphate & soda-lime container glass with 30% replacement as it was with 20% replacement. Soda-lime container glasses was either the sixth strongest or the weakest glass type for this replacement level; only at 6 months did it end up becoming the fourth strongest glass type.

To better understand glass powder as a pozzolan, a comparison between the compressive strengths of the mortars and various compositional parameters were examined. These components consisted of comparing compressive strength to w/cm ratio, CaO content, $SiO_2+Al_2O_3+Fe_2O_3$ content, and $Na_2O_{(eq)}$ content for 20 and 30% replacements at 28 and

90 days. They were analyzed due to the way they each effect the mixture's hydration phases and products. $Na_2O_{(eq)}$ amount is prevalent in glass powder and could affect compressive strength (Shi and Zheng, 2007; Du and Hwee Tan, 2015; "Recycled Glass", 2005; Kamali and Ghahremaninezhad, 2016) These results will be talked about in the following sections.

4.3.3.1 Early Strength

This section compares early strength data from 1, 7, and 28 day breaks and provides further discussion on the 28 day results between 20 and 30% replacement levels. 28 day results were selected due to this break day being an important factor in determining how strong a mixture's early strength is.

For 20% replacement, only one glass type, TV/CRT panel and soda-lime container glass, or sample H, did not pass the 75% SAI requirement at 7 days. This low strength for sample H could be due to the correlation of glass H having a $SiO_2+Al_2O_3+Fe_2O_3$ less than 70%. At 28 days, sample H met the strength requirement, but the aluminosilicate and glass ceramic, or sample D, failed to have a SAI of 75%. Sample D could have seen a strength drop due to poorly formed hydration phases and products. Excluding these two glass types at their corresponding failed break day, all the glass types at 20% replacement had a SAI of at least 75% from 7 to 28 days with some in the high 80's, 90's and low 100's. Remember, being higher than 100% SAI indicates that the sample had a higher

compressive strength than the portland cement control. Only E-Glass and soda-lime plate glass had a SAI of at least 75% at 1 day.

For the 30% replacement level, most glass types did not have a SAI of 75% at 7 or 28 days. During this early period, E-Glass was the only type that met this strength requirement at 7 days. At 28 days only soda-lime container and plate glass, soda-lime plate glass, phosphate and soda-lime container glass, and E-Glass passed with a SAI of at least 75%. From 7 to 28 days, only two samples, Q and T, had a SAI of at least 80%.

Focusing on the 28 day break data will help provide a better idea of how factors like composition and w/cm ratio affected the glasses' compressive strength. Figure 4.13 shows 20 and 30% SAI for each glass and how they compare to the control and fly ash samples. In this figure, all the glasses are color coded to indicate what glass type they fall under with the main purpose to show how strength can differ not only between different glass types, but within the same glass type. The differences between the same glass type could be due to many factors such as slight differences in composition or contaminants. Table 4.11 and Table 4.12 are similar to the tables shown in Section 4.3.3 with the only difference being that they focus on 1 day thru 28 days. This will help provide a close numerical comparison between Figure 4.13 and those two tables.

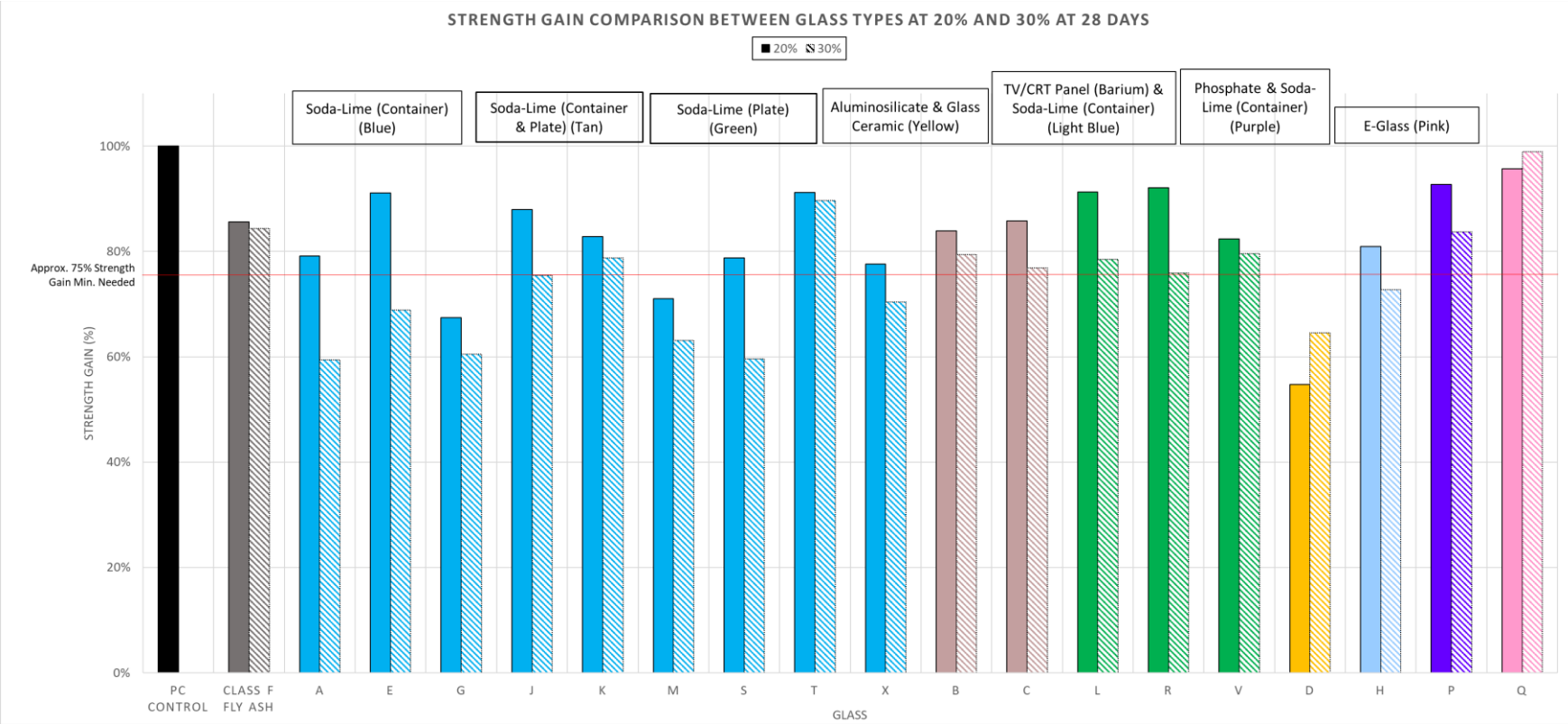


Figure 4.13. SAI comparison between control samples and glass types at 28 days for 20 and 30% replacement.

Table 4.11. Average early SAI at 20% of glass types and control samples from 1 day to 28 days.

*Red indicates that sample type did not meet 75% SAI minimum	**Average 20% SAI at 1 day (%)**	**Average 20% SAI at 7 days (%)**	**Average 20% SAI at 28 days (%)**
Soda-Lime Glass (Container)	69	76	81
Soda-Lime Glass (Container and Plate)	73	80	85
Soda-Lime Glass (Plate)	76	83	89
Aluminosilicate Glass & Glass Ceramic	60	80	55
TV/CRT Panel (Barium) & Soda-Lime Glass (Container)	70	73	81
Phosphate & Soda-Lime Glass (Container)	72	78	93
E-Glass	81	87	96
Portland Cement	100	100	100
Class F Fly Ash	75	87	86

Table 4.12. Average early SAI at 30% of glass types and control samples from 1 day to 28 days.

*Red indicates that sample type did not meet 75% SAI minimum	**Average 30% SAI at 1 day (%)**	**Average 30% SAI at 7 days (%)**	**Average 30% SAI at 28 days (%)**
Soda-Lime Glass (Container)	57	65	70
Soda-Lime Glass (Container and Plate)	59	70	78
Soda-Lime Glass (Plate)	63	69	78
Aluminosilicate Glass & Glass Ceramic	58	69	65
TV/CRT Panel (Barium) & Soda-Lime Glass (Container)	56	65	73
Phosphate & Soda-Lime Glass (Container)	68	71	84
E-Glass	70	83	99
Portland Cement	100	100	100
Class F Fly Ash	68	76	84

The following four sections will show the relationship between early compressive strength values to w/cm ratio, CaO content, $SiO_2+Al_2O_3+Fe_2O_3$ content, and $Na_2O_{(eq)}$ for 20 and 30% replacement level, respectively. Each graph shows how each glass sample compared to each other. By looking at each figure and examining the data points as a whole and not as individual samples, some connections were able to be made, but nothing stood out as a large contributing factor. Even with these relationships seeming to not play a lot factor into the sample's compressive strength, they more than likely still had a slight impact on the final test results. With no strong connection being made, it shows that there could be other relationships affecting the compressive strength more than these four looked at. By looking at each data point as an individual sample, some differences are noticed between 20 and 30% figures. By evaluating the data this way, it makes it difficult to make the connection that the variable significantly affected the compressive strength for that sample since only one data point is being evaluated at that time. It is also important to note that during early curing stages of these samples, hydration phases and products are being developed to help make a compact and tight structure.

4.3.3.1.1 Water to Cementitious Material Ratio (w/cm)

The workability of concrete or mortar depends on the mixture's w/cm ratio. Too high or low of a w/cm ratio and the mixture could have strength and property problems. Therefore, it was important to have a flow value within 5% of the control sample. By looking at Figure 4.14 and Figure 4.15, some correlations can be made about how much the w/cm ratio affected the compressive strength of these samples. With the data points being all over the place and not seeing points increase or decrease linearly between

compressive strength and w/cm ratio, it indicates that w/cm ratio did not play a big role in the compressive strength results for both replacement levels. The effect w/cm ratio would have on 20% replacement level versus the 30% replacement level would be different due to the amount of glass powder and portland cement added to each mix indicating w/cm ratio would at least have some effect on the final compressive strength values.

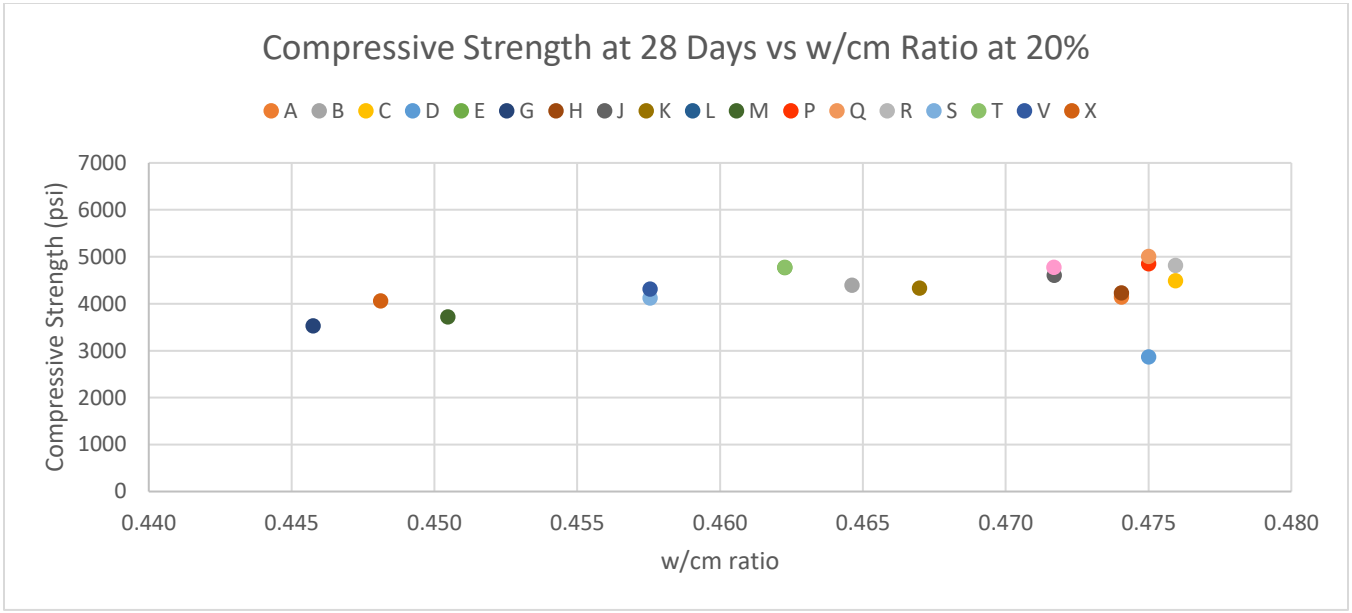


Figure 4.14. Compressive strength at 28 days vs w/cm for glass samples at 20% replacement.

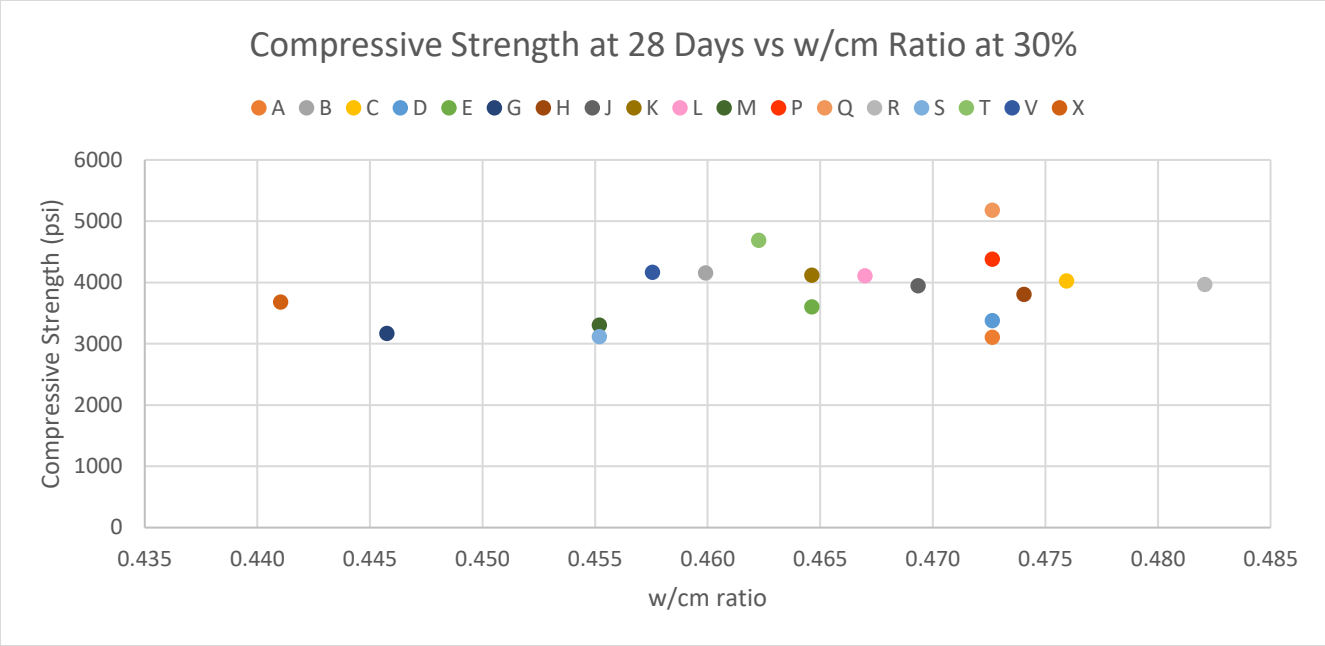


Figure 4.15. Compressive strength at 28 days vs w/cm for glass samples at 30% replacement.

4.3.3.1.2 CaO Content

CaO is important to examine due to its contribution of forming strong hydration phases like C-S-H. Figure 4.16 and Figure 4.17 show the affect CaO had on the compressive strength of the 20 and 30% replacement level samples, respectively. When excluding a few outliers, the data points on both graphs almost form an increasing to decreasing line. At 20% replacement level, the data points seem to increase up to about 10%, then there is no change, and then there is a decrease from about 11.1%-11.5%. At 30% replacement level, the data points seem to increase up to about 8.7% and then decrease from about 9.8%-11.5%. Besides for this little relationship noticed, the data points are somewhat scattered indicating that CaO did not play a big role in the compressive strength results at both replacement levels.

The effect CaO would have on 20% replacement level versus the 30% replacement level would be different due to the amount of glass powder and portland cement added to each mix indicating CaO would at least have some effect on the final compressive strength values. CaO amount might have a smaller impact on 20% replacement levels since more portland cement is in the mixture providing more CaO than the 30% replacement level samples. With CaO being lower in 30% replacement levels, it could become a contributing factor to compressive strength results since hydration products are not able to properly form. This could indicate that the higher the portland cement replacement is with glass powder, the more the CaO amount contributes to determining the sample's strength; if there is nothing else in the sample's composition to help maintain its strength.

Sample P is a good example for the last sentence. This sample is a phosphate and soda-lime container glass with only CaO contributing 6.34% its total composition; this sample has the lowest CaO amount of all the samples. This indicates that for some samples possibly something else in its composition, which would be phosphate in this sample, could help replace the missing CaO by forming different but strong phases. Besides the possibility of something else contributing to a sample's strength, the hydration phases need a large enough CaO content in the mixture to properly form bonds. If the glass doesn't have a high enough CaO amount, the sample could create weak bonds. The one glass sample that performed well at 30% was sample Q, which is an E-Glass. E-Glasses have a large amount of CaO in their composition meaning that it can help replace the CaO lost from taking out more portland cement.

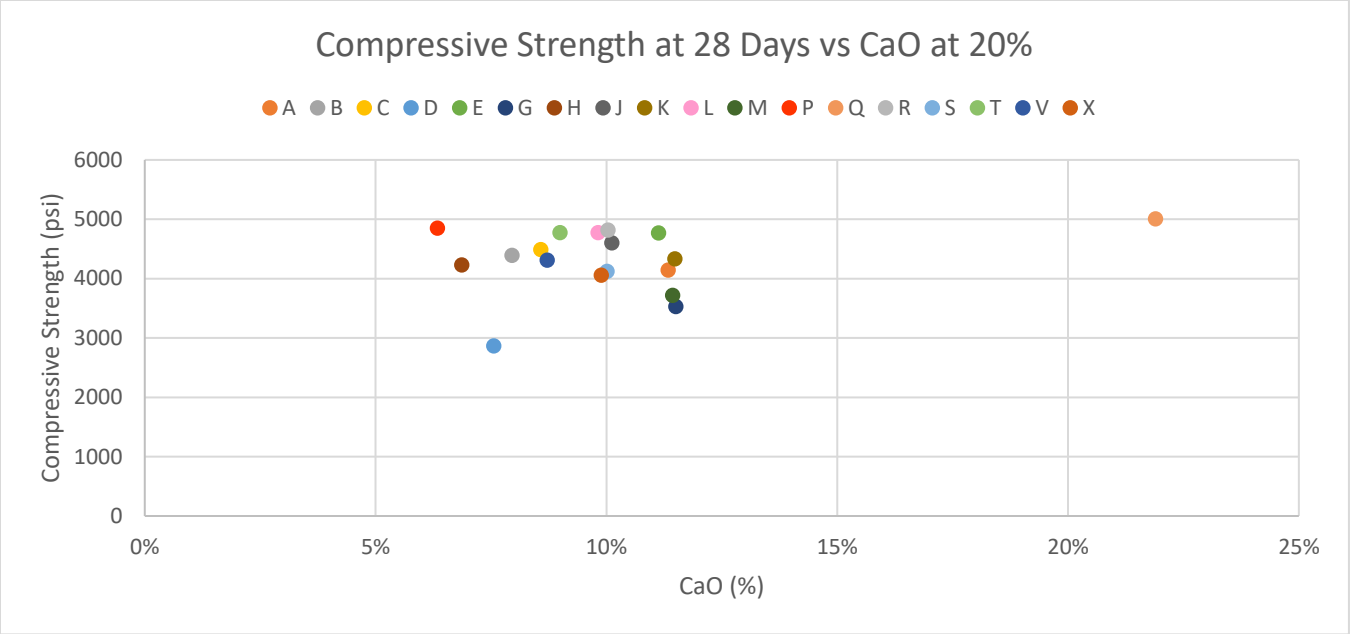


Figure 4.16. Compressive strength at 28 days vs amount of calcium oxide for glass samples at 20% replacement.

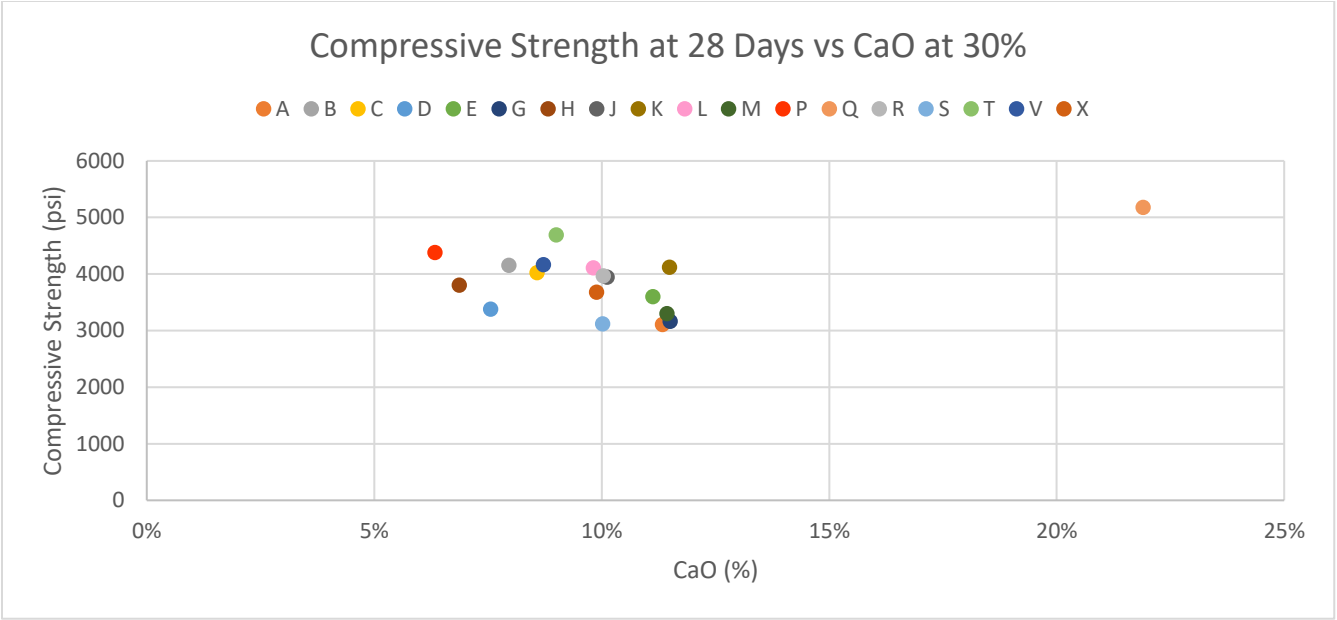


Figure 4.17. Compressive strength at 28 days vs amount of calcium oxide for glass samples at 30% replacement.

4.3.3.1.3 Sum of the Oxides

The sum of oxides is known as the total amount of SiO_2+Al_2O_3+Fe_2O_3 making up a sample's composition. These oxides are important in the formation of hydration phases, in particular the formation of C-S-H through the pozzolanic reaction. By looking at Figure 4.18 and Figure 4.19, some correlations can be made about how much the sum of the oxides affected the compressive strength of these samples. For both replacement levels, the data points slightly form a linear relationship at the sum of the oxides increases; excluding a few outliers. This relationship is more noticeable in the 20% replacement than the 30% replacement indicating that sum of the oxides possibly played a larger role in the 20% replacement level strengths. In the 20% replacement level graphs, the first two data points increase, then start to decrease, but then instantly increases again up until about 74.3% until it finally starts to decrease again. For the 30% replacement level graph, there was a linear relationship noticed between 72% to either about 74.9% or about 79%. From 72% to about 73%, there was an increase in data points. On one relationship, there is a decrease in the data points from about 73% to about 74.6%. On the other path, the data points stop decreasing at about 73.7%, increase until about 75.6%, and then decrease again to about 79%.

Since these relationships noticed in each graph do not involve all the data points, it indicates that the sum of the oxides did not play a big role in the compressive strength results for both replacement levels, but again it possibly played a larger role in the 20% replacement level due to more data points forming a clear relationship than the 30% replacement level. The effect sum of the oxides would have on 20% replacement level

versus the 30% replacement level would be different due to the amount of glass powder and portland cement added to each mix indicating sum of the oxides would at least have some effect on the final compressive strength values.

A 20% replacement level could be more affected with the final oxide amount than the 30% replacement level at 28 days due to the mixture having more portland cement than glass powder. Having glass powder in the mixture would provide more of these oxides than a portland cement mixture does due to glass powder having high amounts of SiO_2 and/or Al_2O_3. At 28 days the samples need as much CaO, SiO_2, and Al_2O_3 to form more C-S-H or C-A-S-H to help make the sample stronger and durable. A 20% replacement level would have less SiO_2 and Al_2O_3 than the 30% replacement level meaning that the sum of the oxides could be more of an issue for 20% than 30%.

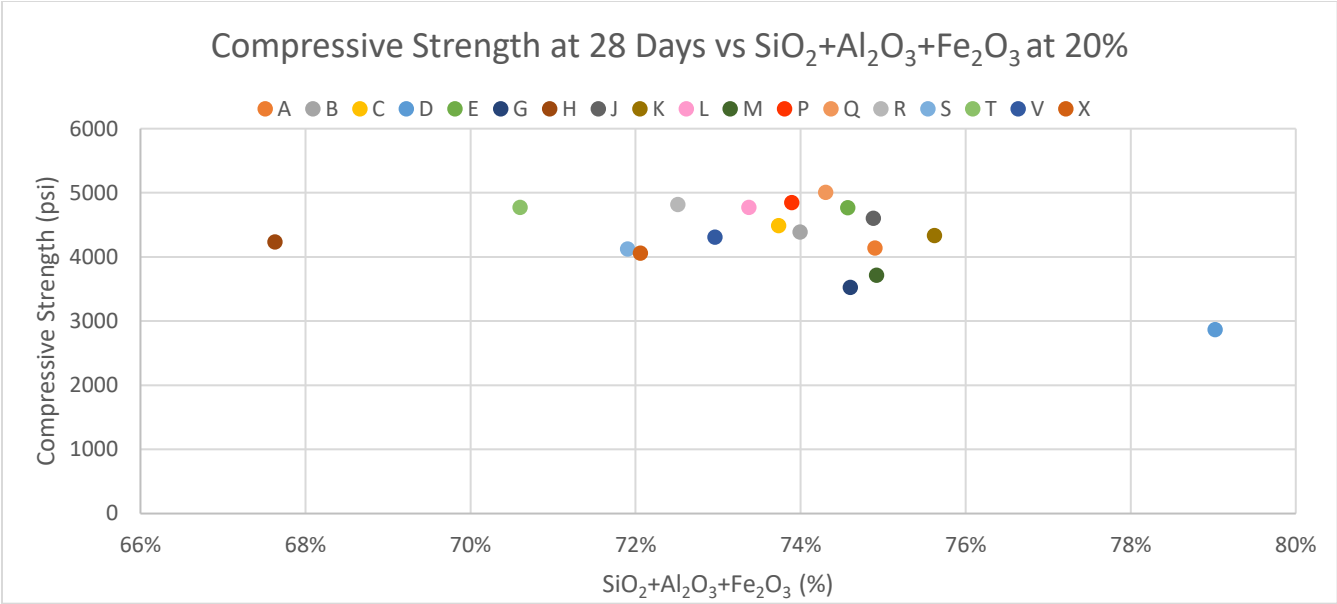


Figure 4.18. Compressive strength at 28 days vs combination of three oxide amounts for glass samples at 20% replacement.

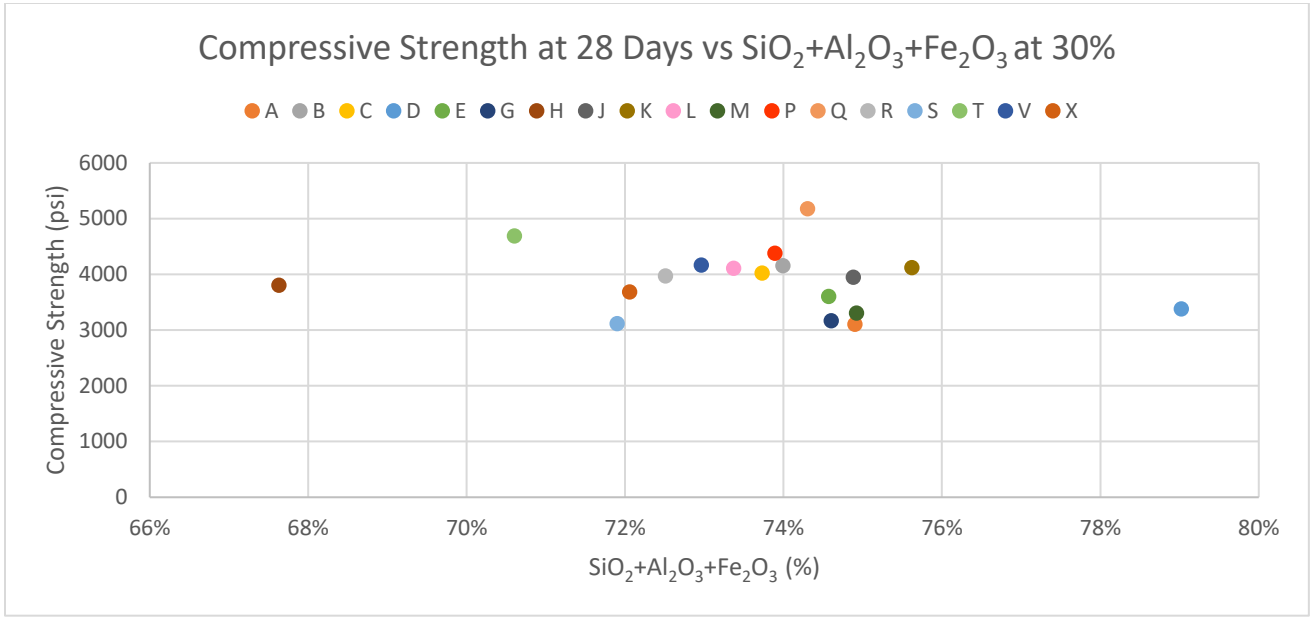


Figure 4.19. Compressive strength at 28 days vs combination of three oxide amounts for glass samples at 30% replacement.

4.3.3.1.4 Sodium Oxide Equivalent

As stated before, glass powder has more alkalis making up its composition than any other pozzolan. Therefore, it is essential to compare $Na_2O_{(eq)}$ amounts for each sample to their compressive strength values. Figure 4.20 and Figure 4.21 show the relationship between $Na_2O_{(eq)}$ and compressive strength for 20 and 30% replacement level, respectively.

$Na_2O_{(eq)}$ did not seem to affect the 20 and 30% replacement levels as much due to a lot of the samples in the 10-12% range being scattered compressive strength values and not forming any type of linear relationship. For the 30% replacement level, the contributing factor from $Na_2O_{(eq)}$ stems from there being more glass powder added. Glass powder is known to have more alkalis within their composition than other pozzolans which could have implications like the formation of ASR. If ASR forms, the samples would become weak and break easily. Shayan and Xu (2006) reported that their samples had no expansion from the possibility that the pozzolanic reaction of the glass powder with the portland cement enhanced the binding of the alkalis. This made the alkalis unavailable for reaction to cause expansion. Knowing that the more glass powder there is in the mix, the higher $Na_2O_{(eq)}$ will be indicates that $Na_2O_{(eq)}$ has a higher chance of effecting a 30% replacement level mixture than a 20% replacement level mixture.

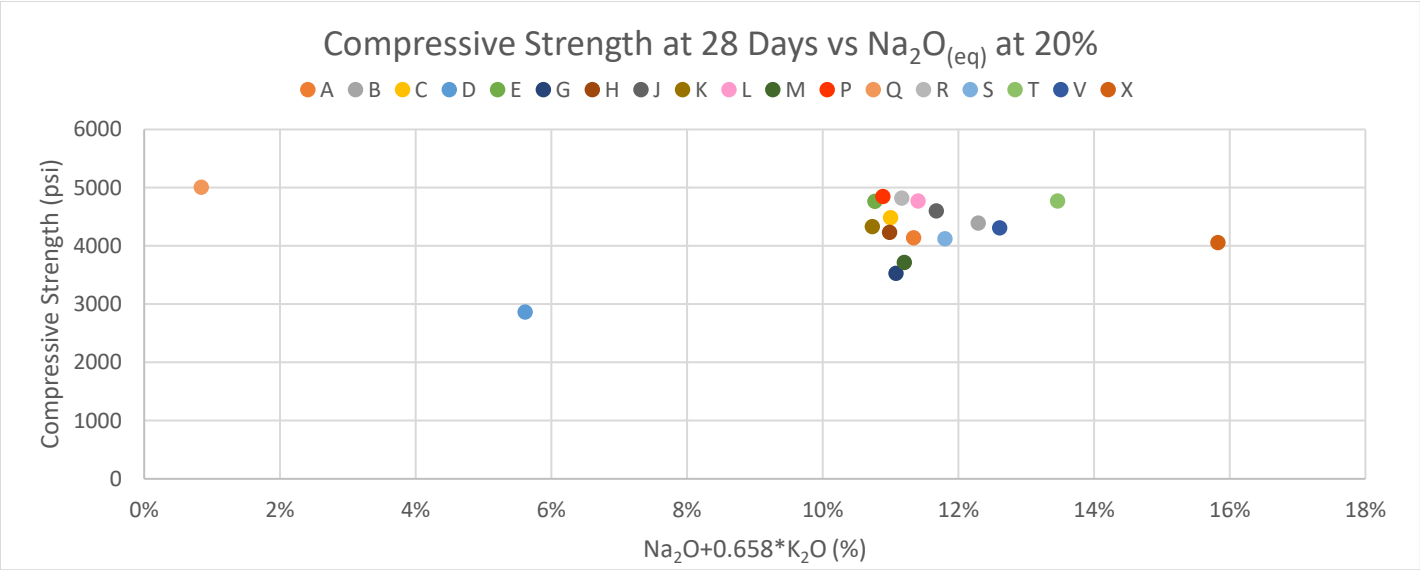


Figure 4.20. Compressive strength at 28 days vs sodium oxide equivalent for glass samples at 20% replacement.

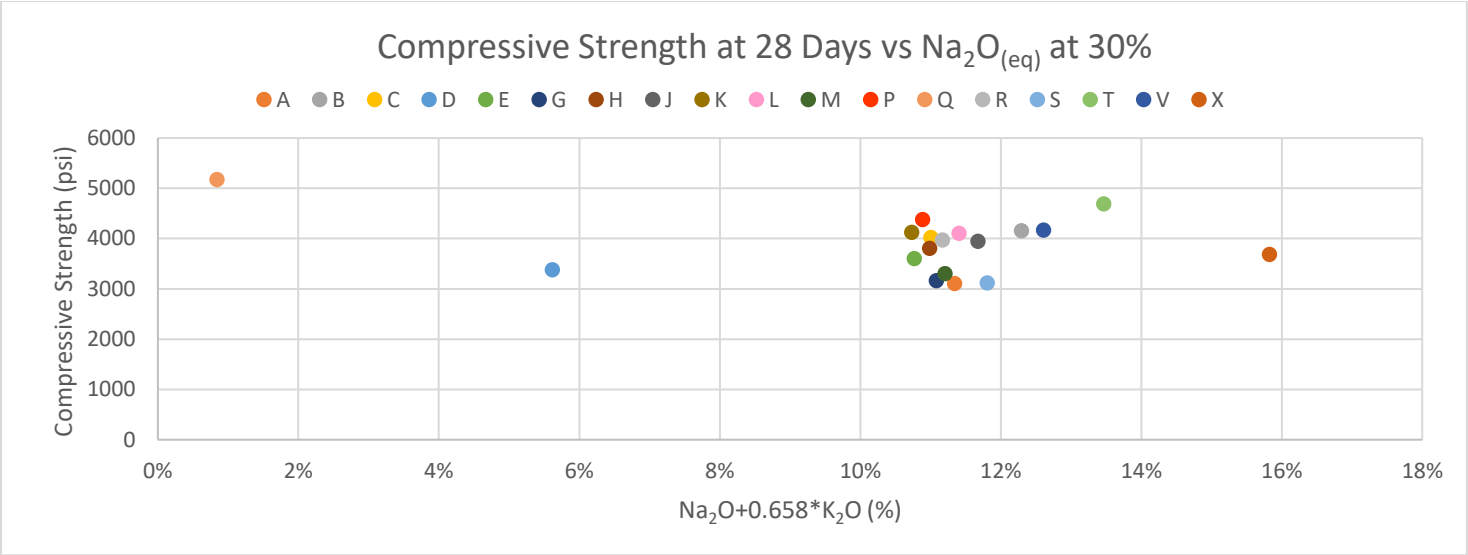


Figure 4.21. Compressive strength at 28 days vs sodium oxide equivalent for glass samples at 30% replacement.

4.3.3.2 Later Strength

This section will compare later strength data from 56 days, 90 days, and 6 month breaks between 20 and 30% and provide further discussion on the 90 day results between the two replacements. 90 day results were analyzed due to this day being an important factor in determining how strong a mixture's later strength is.

For the mixtures with a 20% replacement, only one glass type, TV/CRT panel and soda-lime container glass, did not pass the 75% SAI requirement at 56 days. Even though this requirement is only looked at from 7 to 28 days, it was important that later day strengths also met this requirement to ensure that hydration phases and products were staying strong and not getting weak. The failed SAI requirement occurred at 56 days, and it was due to sample H having a strength loss between 28-90 days. There could be a correlation in sample H having strength problems due to it having an $SiO_2+Al_2O_3+Fe_2O_3$ less than 70%. Excluding that one glass type, all the glass types at 20% replacement had a SAI of at least 80% from 56 days to 6 months with some in the high 90's and low 100's. Remember, being higher than 100% SAI indicates that the sample had a higher compressive strength than the portland cement control.

For the mixtures containing a 30% replacement, most soda-lime container glasses and TV/CRT panel and soda-lime container glass did not pass at 56 and 90 days. During this later day period, E-Glass, soda-lime plate glass, and the phosphate and soda-lime container glass were the only three that had a SAI of at least 82%; E-Glass did end up

with a value over 100%. From 56 days to 6 months, the rest of the samples barely reached 80% SAI.

Focusing on the 90 day break data will help provide a better idea of how factors like composition and w/cm ratio affected the glasses' compressive strength. Figure 4.22 shows 20 and 30% SAI for each glass and how they compare to the control and fly ash samples. All the glasses are color coded to indicate what glass type they fall under, but the main purpose of color coding is to show how even strength can differ not only between different glass types, but also within the same glass type. This difference between the same glass types could be due to many factors like composition and contaminants. Table 4.13 and Table 4.14 are similar to the tables shown in section 4.3.3 with the only difference being that they focus on 56 days thru 6 months. This will help provide a close numerical comparison between Figure 4.22 and those two tables.

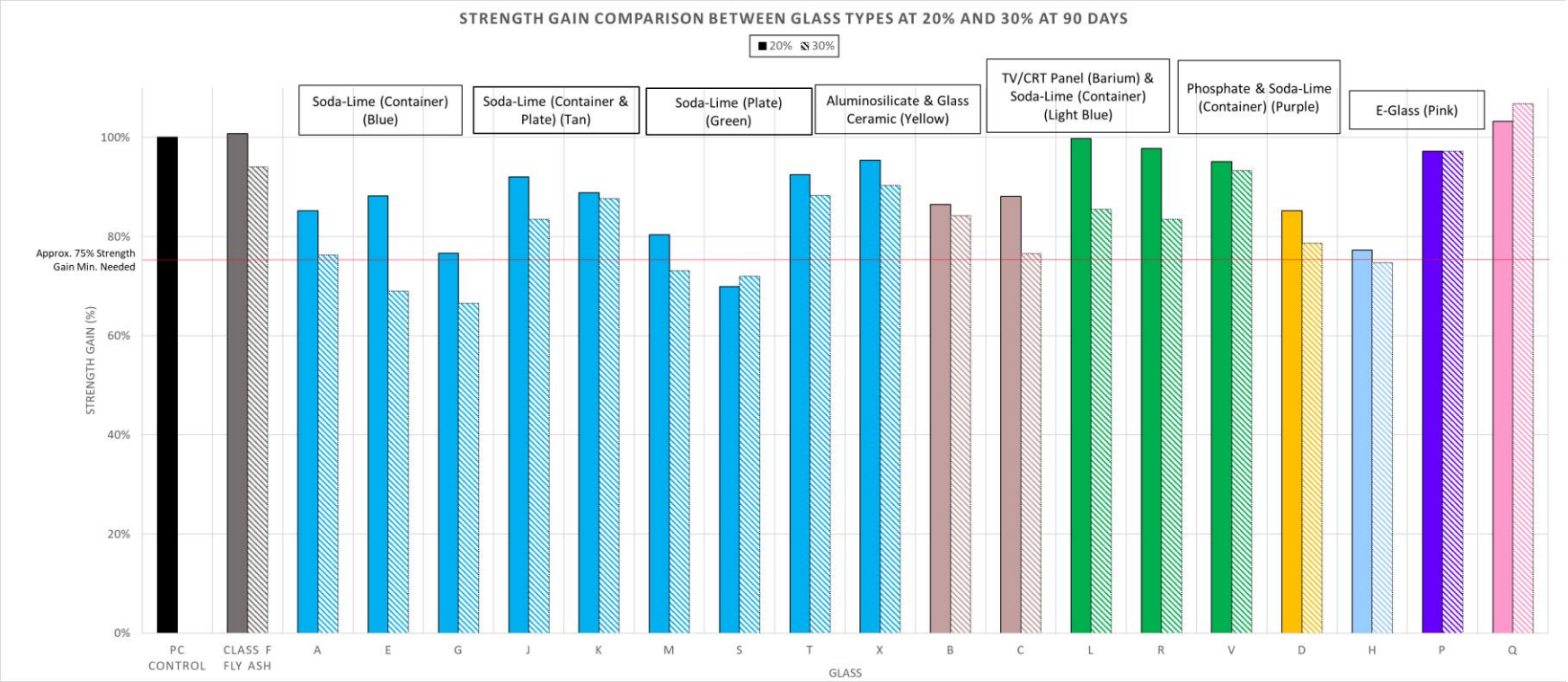


Figure 4.22. SAI comparison between control samples and glass types at 90 days for 20 and 30% replacement.

Table 4.13. Average later SAI at 20% of glass types and control samples from 56 days to 6 months.

*Red indicates that sample type did not meet 75% SAI minimum	**Average 20% SAI at 56 days (%)**	**Average 20% SAI at 90 days (%)**	**Average 20% SAI at 6 months (%)**
Soda-Lime Glass (Container)	84	85	89
Soda-Lime Glass (Container and Plate)	87	87	89
Soda-Lime Glass (Plate)	96	98	98
Aluminosilicate Glass & Glass Ceramic	84	85	88
TV/CRT Panel (Barium) & Soda-Lime Glass (Container)	70	77	91
Phosphate & Soda-Lime Glass (Container)	102	97	93
E-Glass	100	103	95
Portland Cement	100	100	100
Class F Fly Ash	97	101	106

Table 4.14. Average later SAI at 30% of glass types and control samples from 56 days to 6 months.

*Red indicates that sample type did not meet 75% SAI minimum	**Average 30% SAI at 56 days (%)**	**Average 30% SAI at 90 days (%)**	**Average 30% SAI at 6 months (%)**
Soda-Lime Glass (Container)	73	79	81
Soda-Lime Glass (Container and Plate)	78	80	80
Soda-Lime Glass (Plate)	83	87	86
Aluminosilicate Glass & Glass Ceramic	81	79	77
TV/CRT Panel (Barium) & Soda-Lime Glass (Container)	77	75	76
Phosphate & Soda-Lime Glass (Container)	91	97	90
E-Glass	107	107	98
Portland Cement	100	100	100
Class F Fly Ash	87	94	95

The following four sections will show the relationship between later compressive strength values to w/cm ratio, CaO amount, $SiO_2+Al_2O_3+Fe_2O_3$ amount, and $Na_2O_{(eq)}$ for 20 and 30%, respectively. By looking at each figure and examining the data points as a whole and not as individual samples, some connections were able to be made, but nothing stood out as a large contributing factor. Even with these relationships seeming to not play a lot factor into the sample's compressive strength, they more than likely still had a slight impact on the final test results. With no strong connection being made, it shows that there could be other relationships affecting the compressive strength more than these four looked at. By looking at each data point as an individual sample, some differences are noticed between 20 and 30% figures. By evaluating the data this way, it makes it difficult to make the connection that the variable significantly affected the compressive strength for that sample since only one data point is being evaluated at that time. During later curing stages, hydration phases and products have been pretty much formed. The main concern in later strength data is ensuring no phases and products broke apart and nothing occurred within the sample that could cause problems: an example being ASR. In later strength development, 20 and 30% can have the same variations affect their compressive strength results, but at different intensities.

4.3.3.2.1 Water to Cementitious Material Ratio (w/cm)

By looking at Figure 4.23 and Figure 4.24, some correlations can be made about how much the w/cm ratio affected the compressive strength of these samples. For 20% replacement level the data points are all over the place and there is not much of an increase or decrease linearly between compressive strength and w/cm ratio. For 30%

replacement level there are still some data points scattered, but there is more of a linear relationship occurring. From a w/cm ratio of 0.441 to 0.482, the data points started to decrease, then increase, then back to decreasing, and slightly start to increase at the end; excluding a few data points that did not fit this trend. This indicates that w/cm ratio possibly had a higher impact on the 30% samples than the 20% samples. The effect w/cm ratio would have on 20% replacement level versus the 30% replacement level would be different due to the amount of glass powder and portland cement added to each mix indicating w/cm ratio would at least have some effect on the final compressive strength values. By 90 days most or all the hydration phases have already been formed but can get stronger if there are still enough water, CaO, SiO_2, and Al_2O_3 able to react. This is why concrete strength can slowly increase over long periods of time.

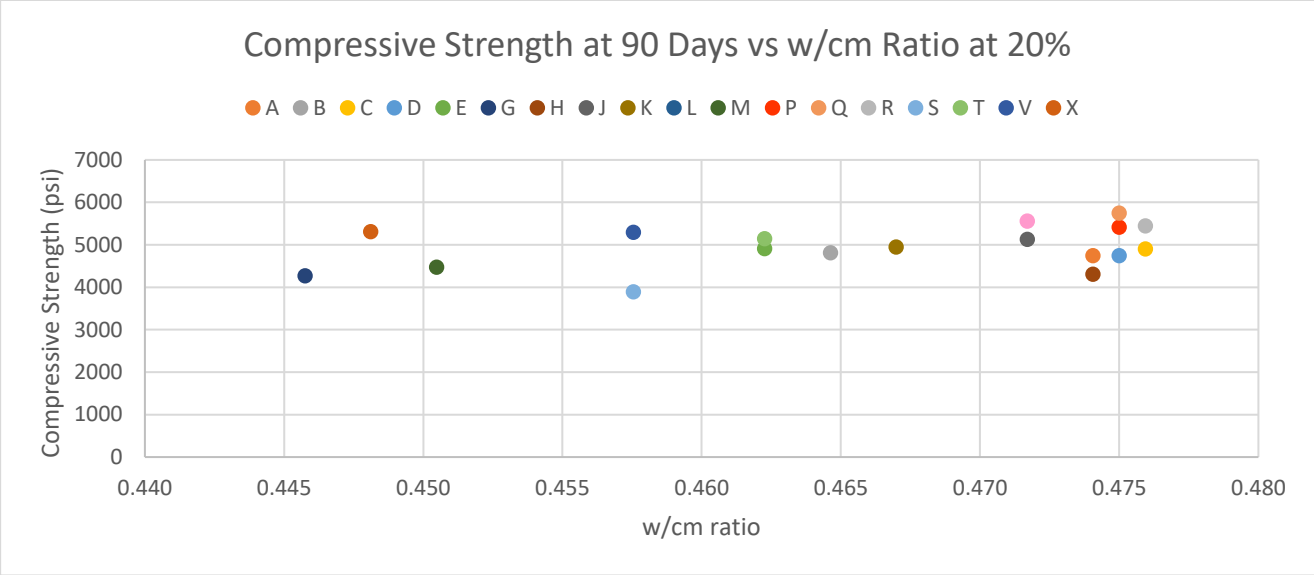


Figure 4.23. Compressive strength at 90 days vs w/cm for glass samples at 20% replacement.

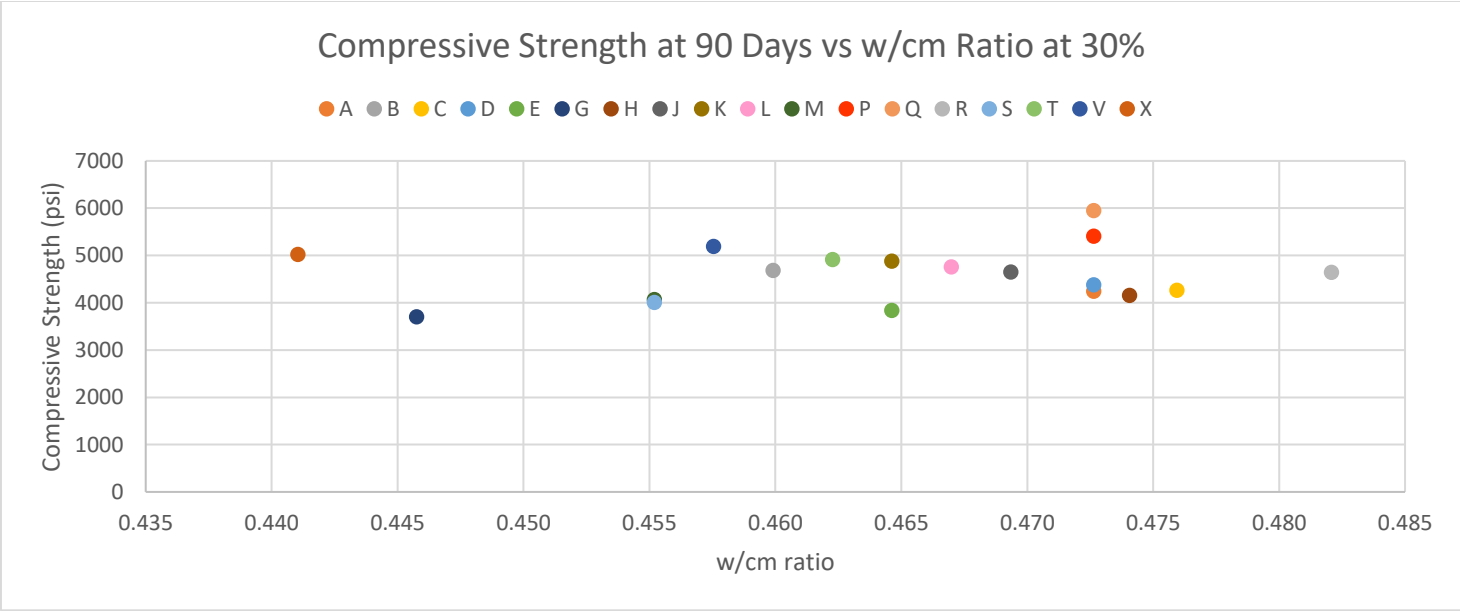


Figure 4.24. Compressive strength at 90 days vs w/cm for glass samples at 30% replacement.

4.3.3.2.2 CaO Content

The interesting thing to notice from Figure 4.25 and Figure 4.26 is that the CaO amount possibly impacted both replacement levels almost equally. The data points in both graphs seem to increase up to about 10% CaO and then start to decrease; with the exception of a few data points. This shows that a CaO amount of around 10% is ideal for most of the glass samples. As a mixture cures, regardless of age, it will always form as much CH, C-S-H, and/or C-A-S-H as possible which can affect the strength values of that sample. The increase in the data points could indicate that if the sample had more CaO, more C-S-H or C-A-S-H could form due to unreacted oxides. The decrease in the data points could indicate that too much CaO and not enough oxides are possibly forming more CH than C-S-H causing boding issues.

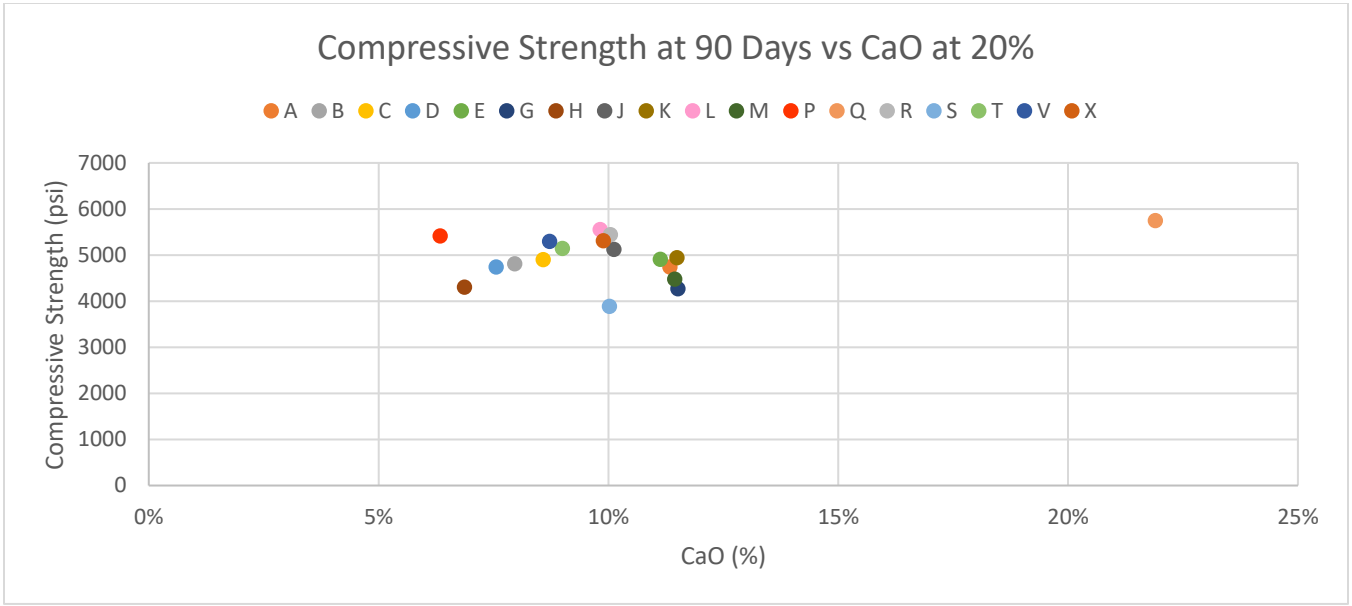


Figure 4.25. Compressive strength at 90 days vs amount of calcium oxide for glass samples at 20% replacement.

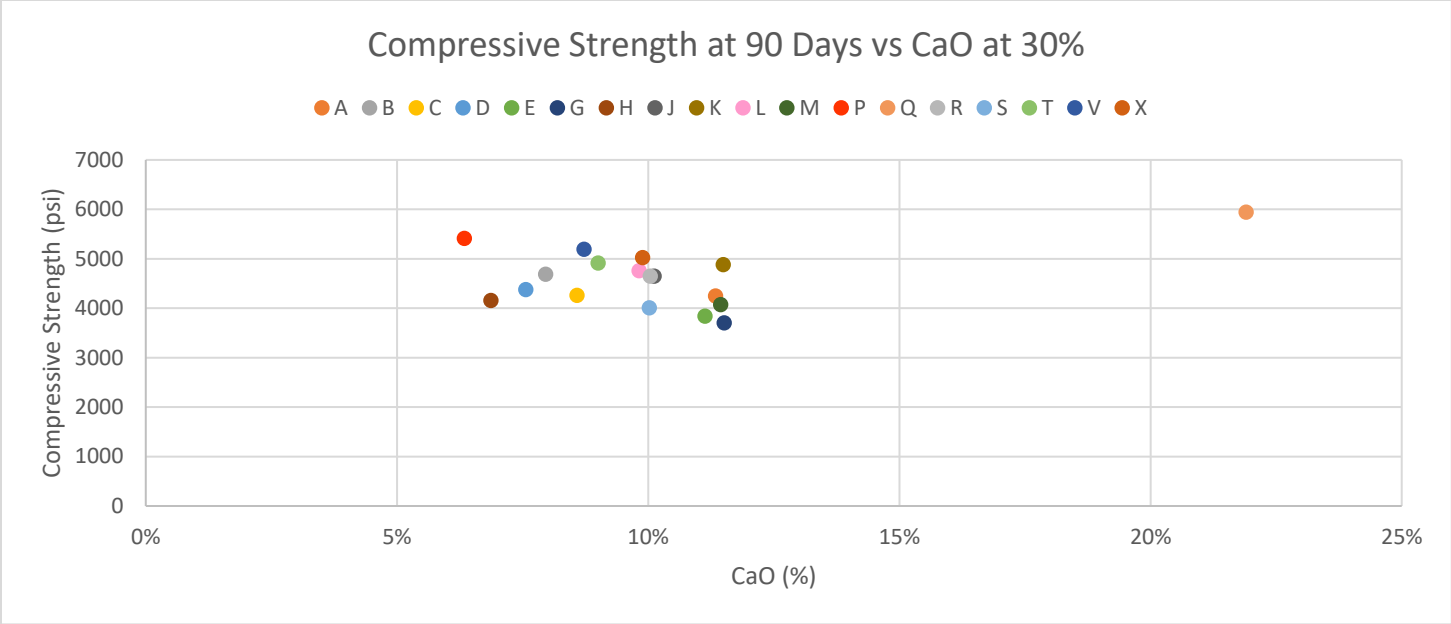


Figure 4.26. Compressive strength at 90 days vs amount of calcium oxide for glass samples at 30% replacement.

4.3.3.2.3 Sum of the Oxides

Figure 4.27 and Figure 4.28 show the sum of the oxides for the 20 and 30% replacement levels at 90 days, respectively. In these figures, there seems to be almost a relationship between the sum of the oxides and compressive strength up until about 73% for both replacement levels. After that, there doesn't seem to be any relationship. This indicates that the sum of the oxides possibly did not play much effect into the compressive strength results at 20 and 30% replacement levels. At later ages, hydration phases tend to slow down or stop indicating that the sum of the oxides would have less of an impact on both replacement levels. SiO_2 and Al_2O_3 still can play an important role in helping more C-S-H or C-A-S-H form which could mean that sum of the oxides possibly played a small role in the compressive strength results, but it was not a large factor at 90 days.

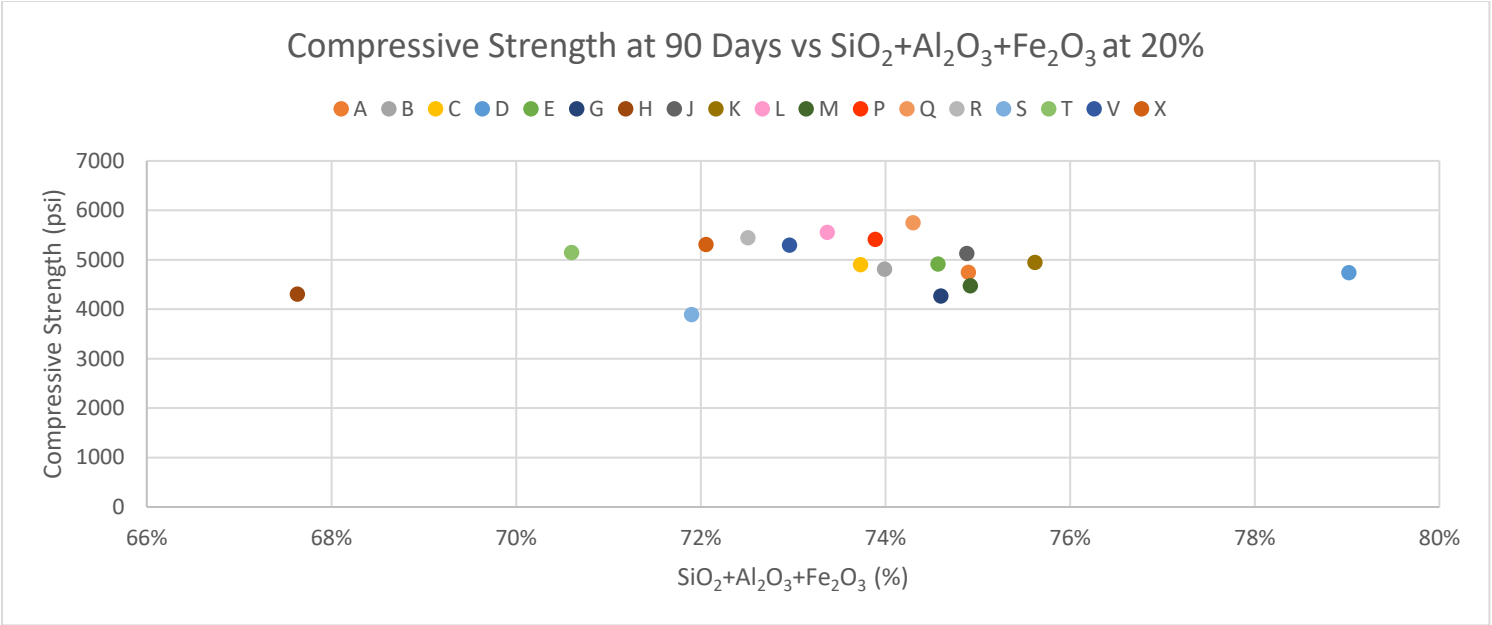


Figure 4.27. Compressive strength at 90 days vs combination of three oxide amounts for glass samples at 20% replacement.

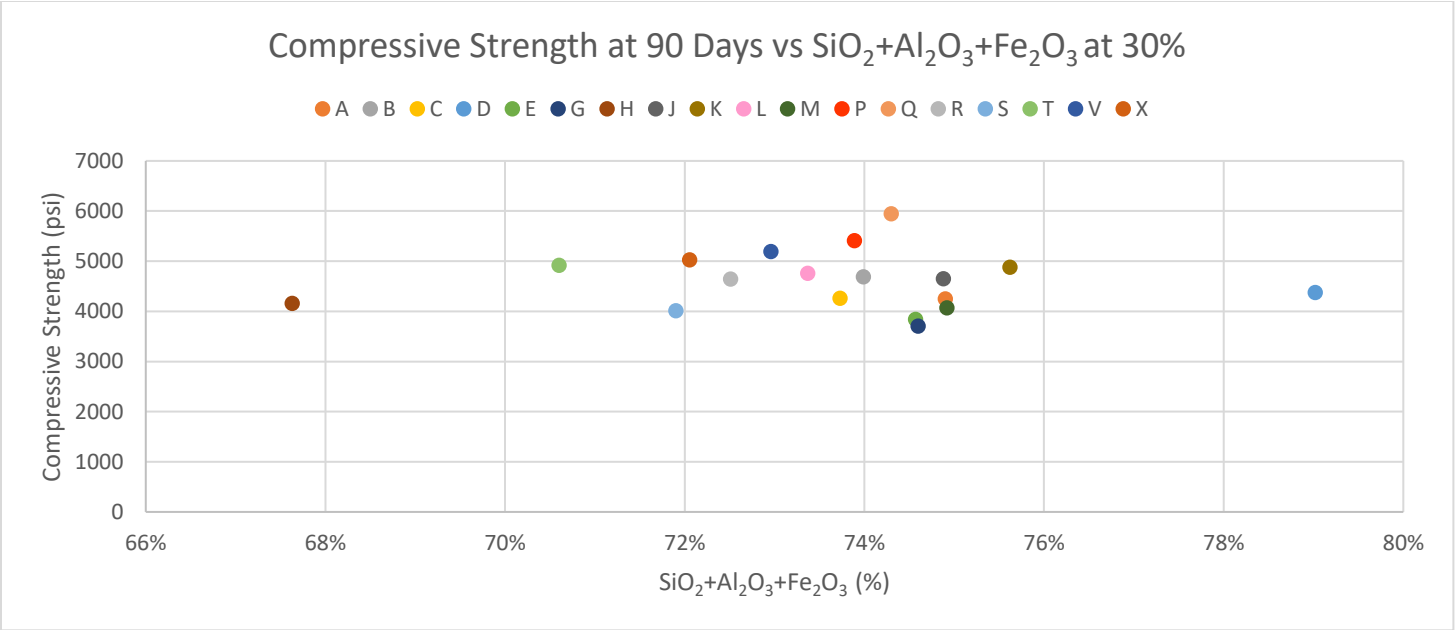


Figure 4.28. Compressive strength at 90 days vs combination of three oxides for glass samples at 30% replacement.

4.3.3.2.4 Sodium Oxide Equivalent

Figure 4.29 and Figure 4.30 shows the comparison between compressive strength and $Na_2O_{(eq)}$. $Na_2O_{(eq)}$ amount at 90 days did not seem to impact the compressive strength results significantly at 20 and 30% replacement levels. The figures show a lot of the data points clumped up near each other between 10-12% with no linear relationship being able to be formed. $Na_2O_{(eq)}$ could become a problem due to high alkali content in the glass powder compositions. Having a high alkali content could cause internal sulfate attacks from ettringite breaking down monosulfates and forming large crystals. These large ettringite crystals make the sample expand and crack causing the sample to become weak. CaO ends up being a large contributing factor to compressive strength due to all or most of the CaO already being dissolved and formed into CH or C-S-H. As samples cure, more C-S-H gel wants to form to help create a stronger bond and make the samples stronger and less likely to be penetrated. If there is more portland cement and glass powder to be dissolved and more water to dissolve it, C-S-H gel will always want to form. For later curing stages of these glass samples, the composition and replacement level can determine how strong of an influence CaO and $Na_2O_{(eq)}$ amount will have on the sample's compressive strength.

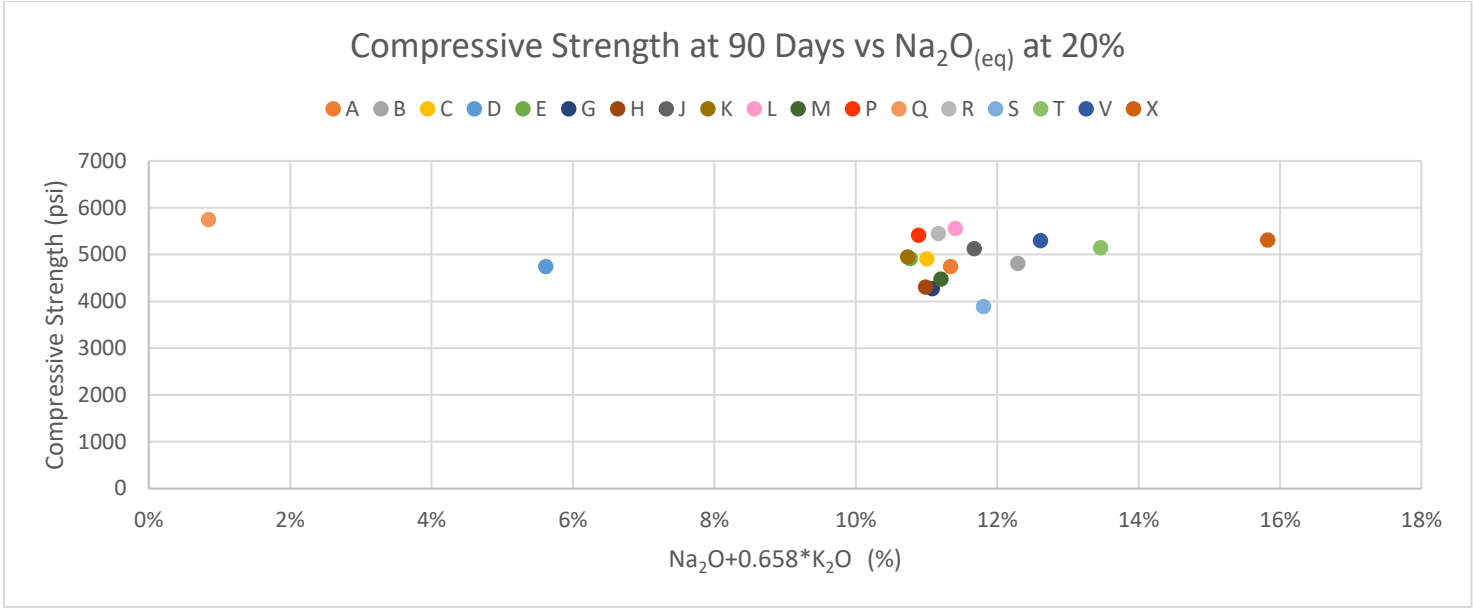


Figure 4.29. Compressive strength at 90 days vs sodium oxide equivalent for glass samples at 20% replacement.

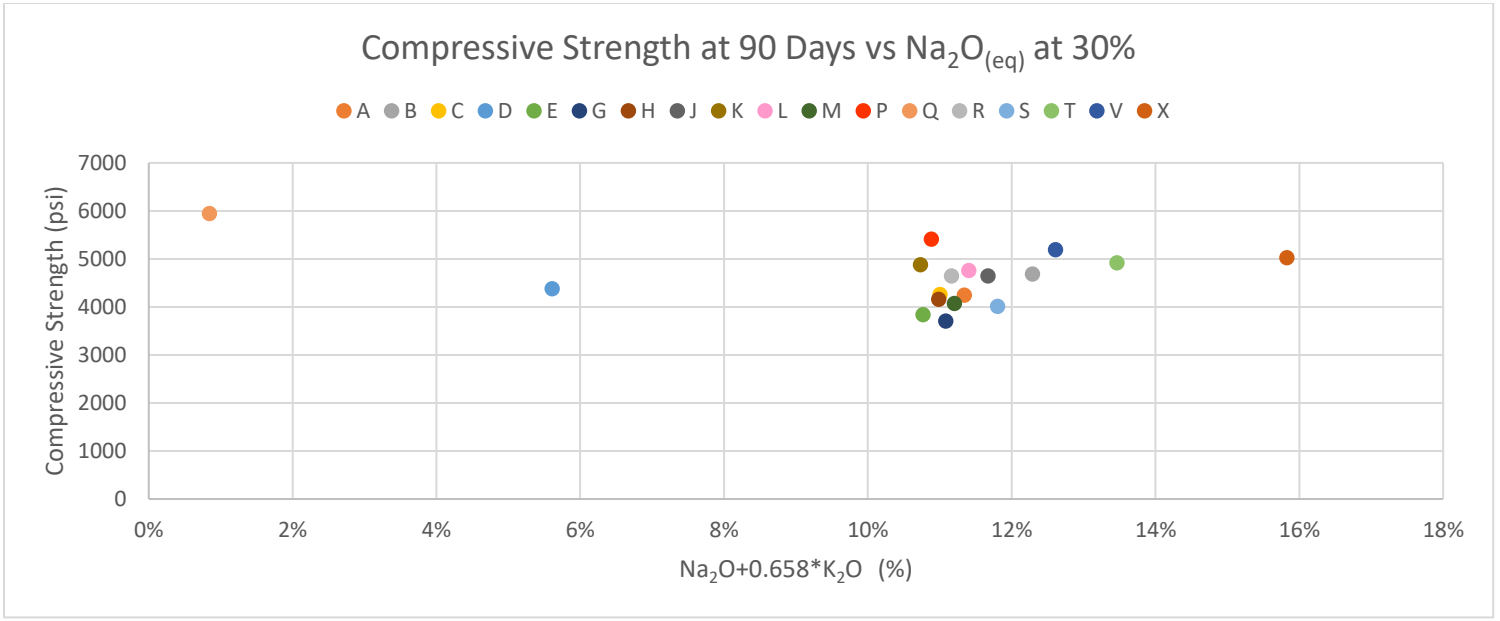


Figure 4.30. Compressive strength at 90 days vs sodium oxide equivalent for glass samples at 30% replacement.

4.3.4 Early Strength vs. Later Strength

It is very important to know how a mixture acts during the early and later ages of its life. From the data already discussed, it is observed that more 20% replacement mixtures fulfill the 75% minimum SAI requirement at 28 days than the 30% replacement mixtures. By 90 days, more 30% replacement mixtures meet this requirement, but a job needing a high early strength would see better and more reliable results with a 20% replacement. It was also observed that almost every glass sample at 20 and 30% replacement made the SAI requirement by 28 days. Soda-lime container glass is the most common type of glass found on the planet, but it also has a wider chemical composition when it comes to classifying a glass as a container glass. Between the compressive strength differences and how each sample became affected by the mixture's w/cm ratio, CaO amount, sum of the oxide amount, and sodium oxide equivalent amount, means that if a glass sample were to be used, it is essential to know what the chemical composition is and ensure it meets the future glass ASTM guidelines before using it in a mixture design.

4.3.5 Hardened Air-Void Structure

As stated before, three mortar cubes each from PC, FA2, Q, S, and T samples were chosen for hardened air-void examination. Before discussing the results gathered from the ImageJ and BubbleCounter programs, some terminology needs to be reviewed. The following definitions and minimum/maximum values can be found between ASTM C457 (2016), ACI 201.2R-08 (2008), and the Significance of Tests and Properties of Concrete & Concrete-Making Materials (ASTM Committee C09, 2006).

Void frequency is the number of voids intercepted by a traverse line divided by the length of that traverse line. It must be a value of 300/m (8/in) or greater to provide good values for specific surface and spacing factor. Specific surface is determined by the air void's surface area divided by their volume. This value is a good way to determine average void size. As average void size goes up, specific surface goes down. A good specific surface value to resist freeze-thaw is 25 mm^2/mm^3 (630 in^2/in^3) or higher. Spacing factor is looked at as a significant indicator of cement paste durability. It measures the largest distance from anywhere in the cement paste to an air void. To resist freeze-thaw for moderate exposure, a value of 0.20 mm (0.008 in) or smaller is needed for spacing factor. Maximum values can increase for mild exposure and can decrease for severe exposures. Smaller values are also needed if the exposure includes deicer chemicals. Air content includes the entrained and entrapped air voids.

It was determined in the Significance of Tests and Properties of Concrete & Concrete-Making Materials (ASTM Committee C09, 2006) that air content was dependent on mixture proportions and increased as nominal maximum aggregate size decreased. For a nominal maximum aggregate size of 4.75mm (No.4), an air content amount to perform well against freeze-thaw was at least 9%. Too high of an air content means a less dense and weak sample, while too low of an air content means a dense sample that will perform poorly in freeze-thaw conditions. Paste content is the total volume that is hardened cementitious paste. Paste to air ratio is the volume of hardened cementitious paste to the volume of air voids. A summary of these definitions and parameters is shown in Table 4.15.

Table 4.15. Important hardened air-void terminology to know.

Term	Parameters	Definition
Void Frequency	≥300/m (8/in)	Number of voids intercepted by a traverse line divided by the length of that line. Good values can provide good surface and spacing factor values.
Specific Surface	≥25 mm^2/mm^3 (630 in^2/in^3)	Determined by the air void's surface area divided by their volume. Can determine average void size.
Average Void Size	-	Correlates with specific surface. As average void size goes up, specific surface goes down.
Spacing Factor	Moderate Exposure: ≤0.20 mm (0.008 in)	Significant indicator of cement paste durability. Measures the largest distance in the cement paste to an air void. As exposure worsens, parameter values become smaller.
Air Content	4.75 mm (No.4) Agg. Size: ≥9%	Dependent on mixture proportions and nominal maximum aggregate size. Too high of an air content means a less dense and weak mixture. Too little of an air content means a dense but will perform poorly in freeze-thaw conditions.
Paste Content	-	Total volume that is hardened cementitious paste.
Paste to Air Ratio	-	The volume of hardened cementitious paste to the volume of air voids.

The average results provided from using the programs ImageJ and BubbleCounter are shown in Table 4.16.

Table 4.16. Average hardened air-void results from the contrast enhanced method.

Sample Name	Average Void Frequency (per/mm)	Average Specific Surface (mm^2/mm^3)	Average Spacing Factor (mm)	Average Air Content (%)	Average Paste Content (%)	Average Paste to Air Ratio
PC	2.3074	36.588	0.025	24.613	17.397	0.845
FA2@20%	2.6411	43.059	0.017	24.593	17.403	0.718
Q@20%	2.5966	40.833	0.018	25.200	17.262	0.714
S@20%	2.8691	51.079	0.016	22.597	17.862	0.798
T@20%	2.9504	60.575	0.016	19.540	18.569	0.958

The following figures show important relationships for a good air-void system. Figure 4.31 shows the relationship between spacing factor and air content. Air content and spacing factor alone cannot determine one or the other, but together can show how much air is in the system and if the spacing is enough with that much air. As said before, spacing factor should be less than 0.20mm and air content, for samples with 4.75mm maximum aggregate size, should be no less than 9%. All the samples meet the requirements needed for spacing factor and air content. The red dash indicating the limit for average spacing factor is not on this graph due to the y-axis only going up to 0.030mm and the limit being less than or equal to 0.20mm.

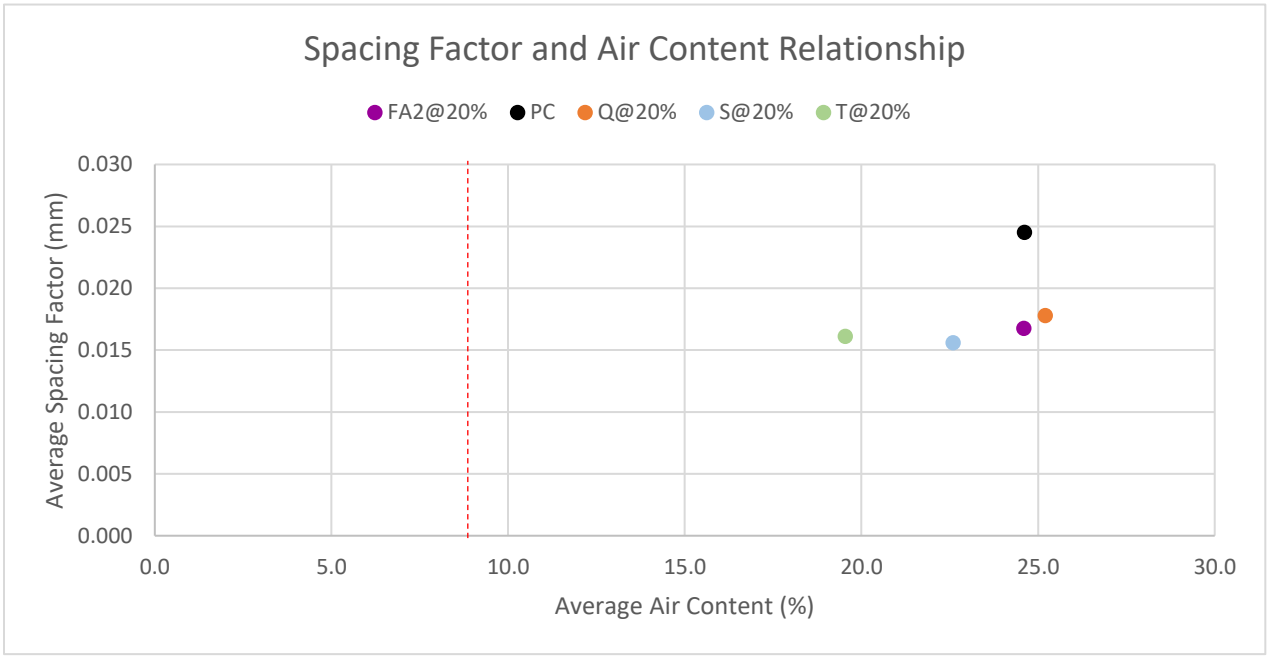


Figure 4.31. Spacing factor and air content relationship with line indicating minimum air content needed for the aggregate used.

Specific surface and spacing factor are another good relationship to compare as shown in Figure 4.32. As air content goes up, it is important that spacing factor is low, and specific surface is high as this indicates that a frequent amount of small air voids are close together to allow water to move throughout the sample as freezing and thawing occur. A high specific surface also means that the sample's density will be large enough to perform well during strength tests. The larger the air voids are, the smaller the sample's density will be. This could result in low compressive strength in these samples.

To reduce damage from freezing and thawing, compressive strength should be no lower than 4000psi (28MPa) (ASTM C457, 2016) before being exposed to repeated freeze-thaw cycles. Figure 4.33 shows that by 6 months, every sample passed this minimum strength requirement. That date was analyzed due to the curing age these samples were at when selected for this test; curing ages ranged from 197 to 300 days. With the air content, spacing factor, and specific surface values all passing their minimum and maximum values, it shows that the samples cured well and ensured a passing compressive strength by 6 months.

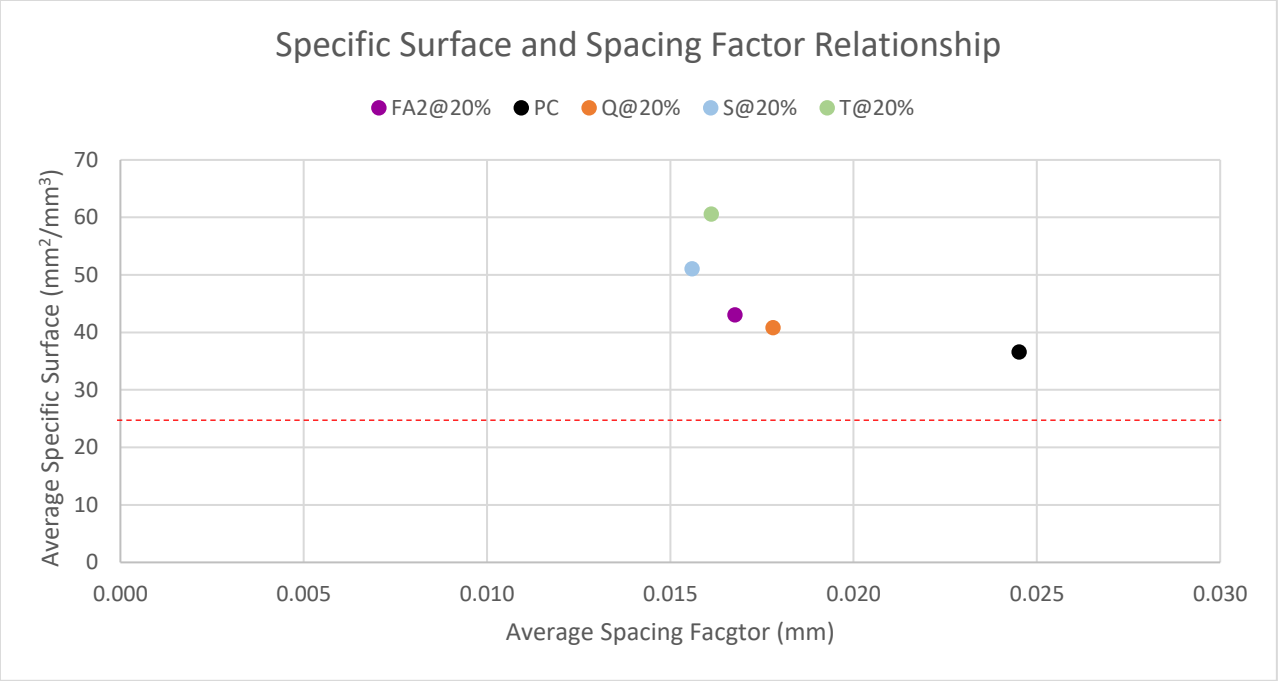


Figure 4.32. Specific surface and spacing factor relationship with horizontal line showing minimum specific surface needed.

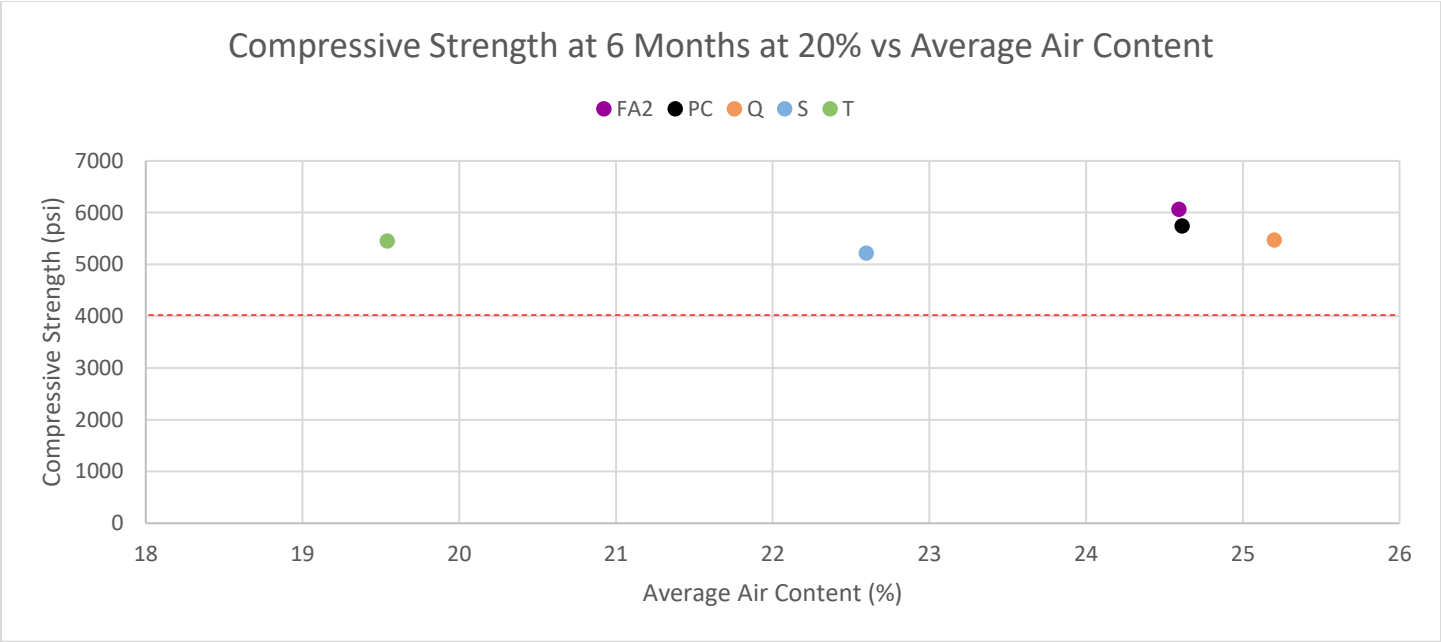


Figure 4.33. Compressive strength at 6 Months and air content relationship with line showing minimum strength needed.

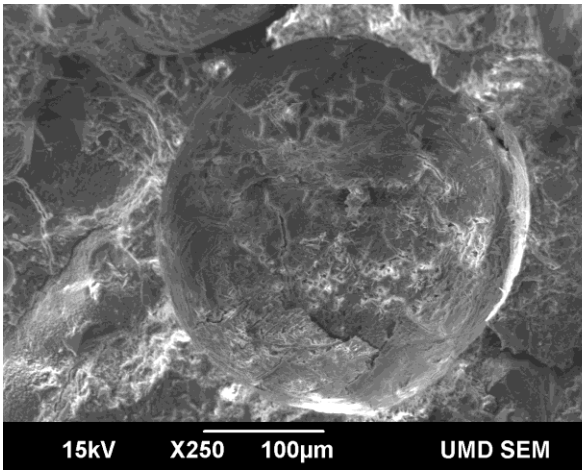
Figure 4.7 and Table 4.5 show that sample S only had a compressive strength of 4000psi or greater on 28 days and 6 months. It is crucial to know how the samples do on each break day to get a better understanding of how durable and well formed the hardened structure is. This shows that S could possibly have trouble combating freeze-thaw damage between 28 days and 6 months. Samples Q and T performed better than sample S. From 28 days and on, samples Q and T had a compressive strength greater than or equal to 4000psi. This indicates that these two samples would meet the strength requirement early on and possibly perform well against freezing and thawing.

4.3.5.1 Hardened Air-Void Summary

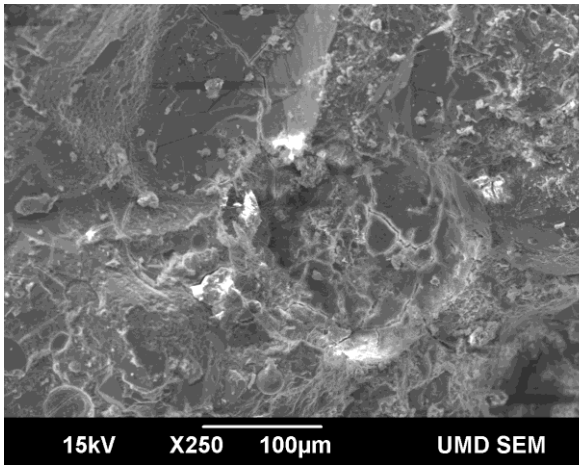
Hardened air-void structure is important to analyze to help determine what the air-void system is within the mixture, and to also provide some preliminary data on how the mixture could perform in freeze-thaw conditions. Just analyzing the glass samples, sample Q had the smallest average void frequency, average specific surface, average paste content, and average paste to air ratio, while having the largest average spacing factor and average air content. Sample T had the smallest average air content but had the largest average specific surface, average paste content, and average paste to air ratio. Samples T and S had the same average spacing factor value otherwise, sample S had values between samples Q and T. Sample Q also had the highest compressive strength value at 6 months followed by samples T and S.

4.3.6 Microstructural Analysis

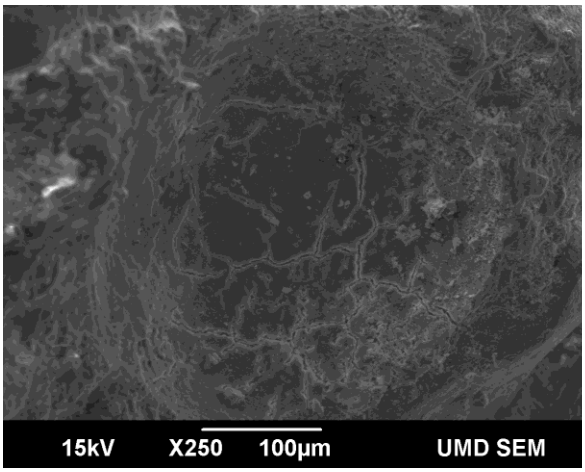
As stated before, samples of PC, Class F fly ash, Q, S, and T were analyzed for microstructural analysis examination. These three glasses where analyzed due to sample Q being an E-Glass with the highest compressive strength between all the glass samples and samples S and T being a soda-lime container glass with the same compositions but very different compressive strength values. For microscopy, SEI, BSE, and EDS examinations were performed. SEI used a fractured surface, while BSE and EDS used a flat, polished surface. Fractured surfaces are used to get a better understanding of the morphology and shape of products. Polished surfaces help provide information on the concrete structure like its porosity, types of phases that occurred, and the composition of selected areas. Each surface examination is dependent for specific examinations and provide more information of what occurred within each sample. To perform a surface analysis, the testing equipment must excite electrons within the sample. The number of electrons that will be excited involve how heavy the elements are within the sample. The types of elements that will show up not only depend on the mixture design but also what phases have formed. To get a slight understanding of the difference between each sample on a microscopic scale, look at Figure 4.34 for a fractured surface at x250 and Figure 4.35 for a polished surface at x100. The microstructure will provide some indication on why these samples performed the way they did.



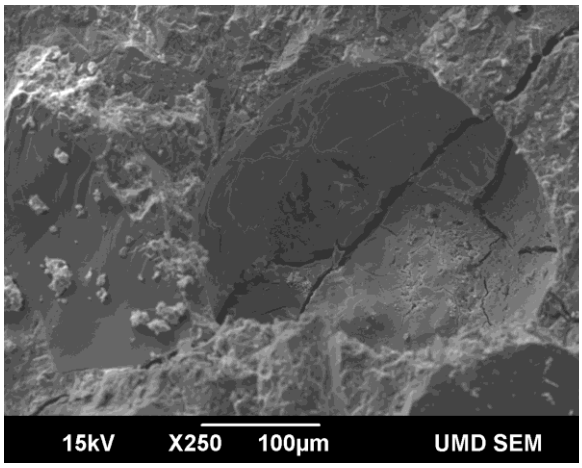
PC Sample



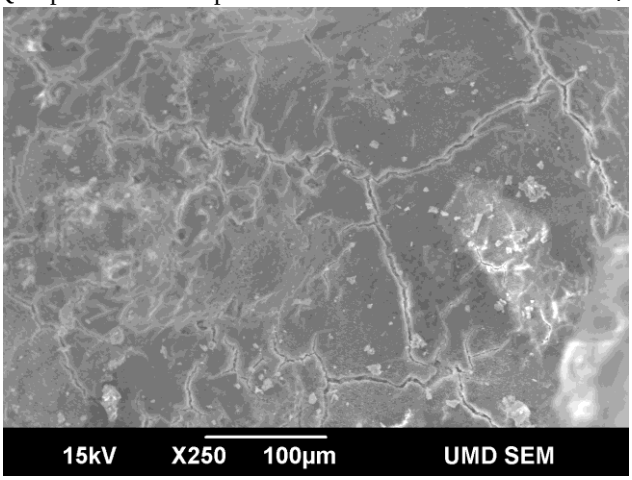
20% Class F Fly Ash Replacement Sample



20% Glass Q Replacement Sample

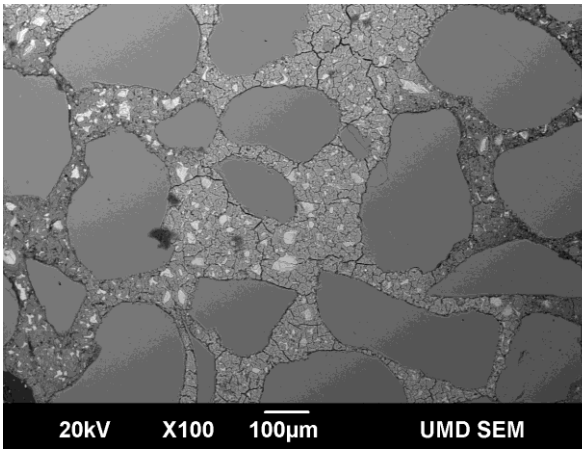


20% Glass S Replacement Sample

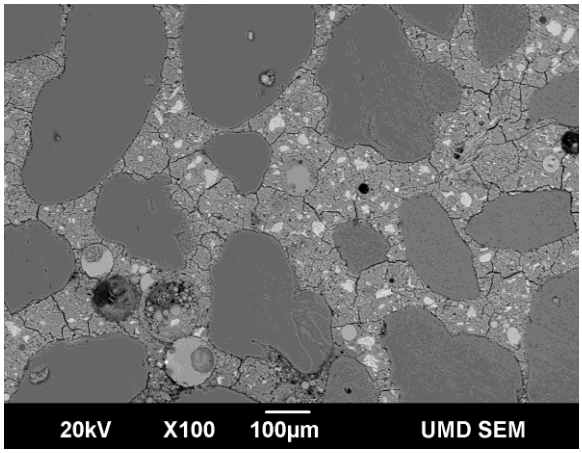


20% Glass T Replacement Sample

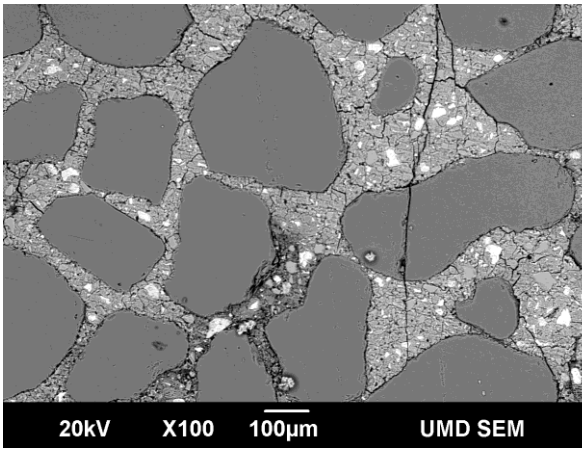
Figure 4.34. One SEI example from each sample at x250.



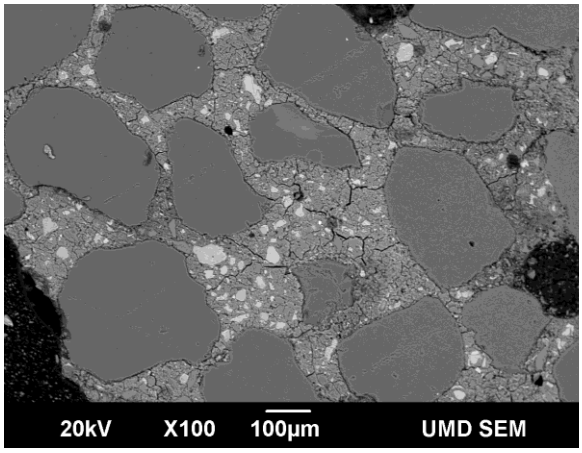
PC Sample



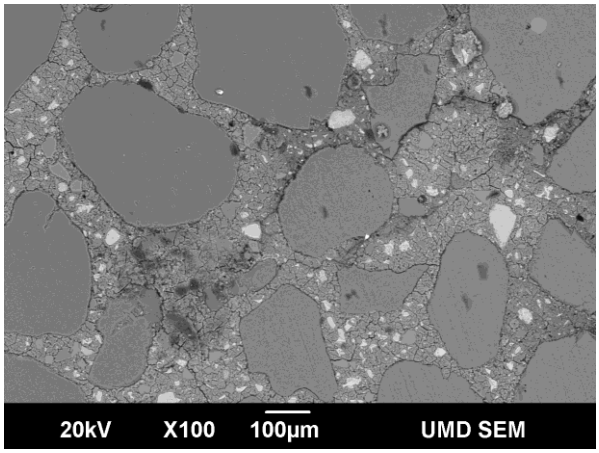
20% Class F Fly Ash Replacement Sample



20% Glass Q Replacement Sample



20% Glass S Replacement Sample



20% Glass T Replacement Sample

Figure 4.35. One BSE example from each sample at x100.

The age of the samples should be the same when comparing samples to each other. However, the older the samples are, the less they change in microstructure. In this case, all samples were older than 90 days, which is typically accepted as the time at which the majority of hydration and pozzolanic reactions have completed. Before being prepared for microstructural characterization, the control was cured for 300 days, the Class F fly ash sample was cured for 299 days, sample Q was cured for of 289 days, and samples S and T were cured for 197 days. It was observed in all the samples with a 20% replacement that very little to no unhydrated cement particles were observed under the microscope. The following sections show the scanning electron imaging (SEI), backscattered electron imaging (BSE), and energy-dispersive spectroscopy (EDS) for all the samples along with callouts indicating what hydration phases and products were detected for each sample.

4.3.6.1 Scanning Electron Imaging

Fractured surfaces from each sample were examined using SEI. Their microstructures show a variety of information like unhydrated particles, cracks, and voids. This is all important to know so that correlations can be made between tests.

4.3.6.1.1 Portland Cement (PC) Sample

Figure 4.36 shows the fractured surface of the control sample. From 1 to 300 days, a small amount of shrinkage was observed from looking at the cube measurements taken each break day. This would indicate a denser sample that would have a chance at

producing a high compressive strength. The microstructure of this sample indicates some cracking around unhydrated portland cement, which would indicate a weak bond in the structure at that location. Unhydrated portland cement particles also indicate that there wasn't enough water left in the system to fully react. As long as the rest of the structure is well formed and enough particles have been fully hydrated, unhydrated particles are not an issue. If there were a lot of unhydrated particles and the compressive strength values were low, this could indicate that not enough water was used in the mixing process. The structure of the sample appears to have little porosity; this is a good sign of the high compressive strength values.

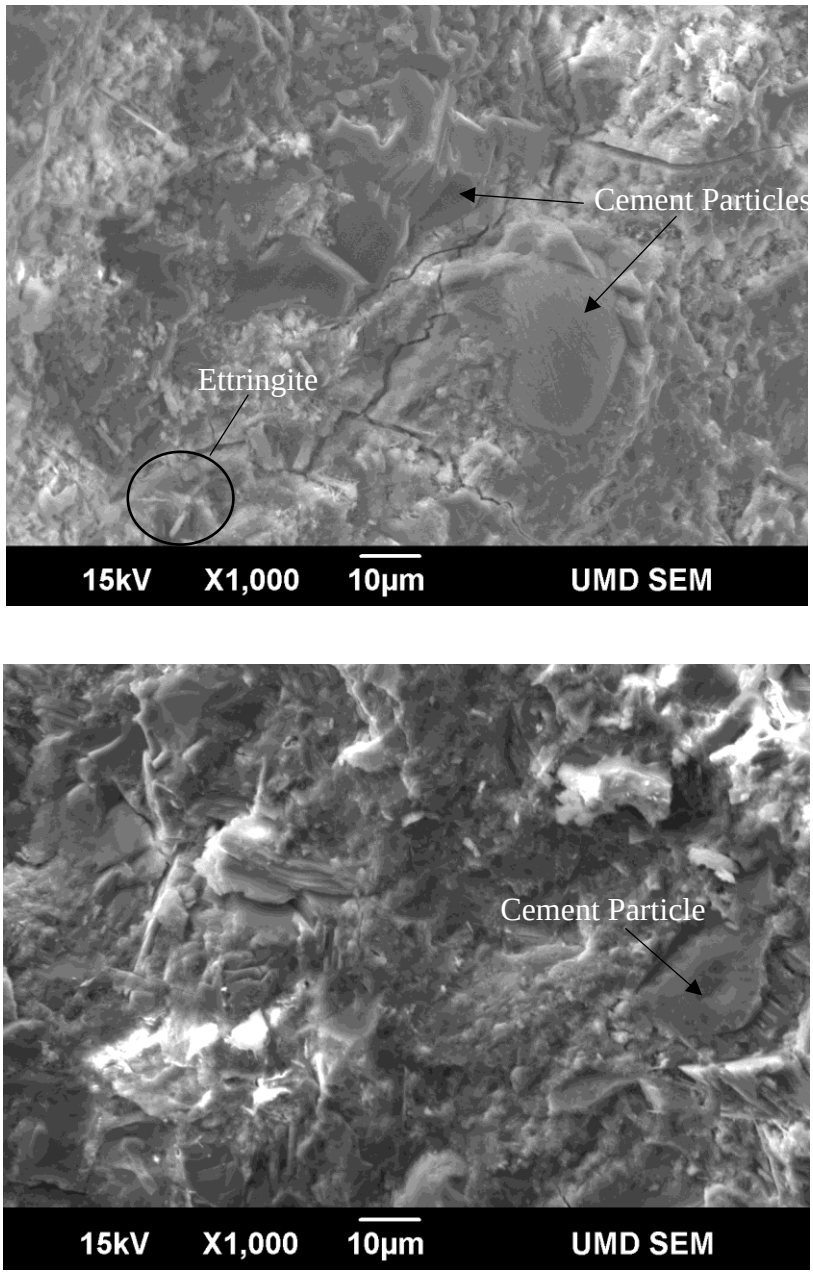
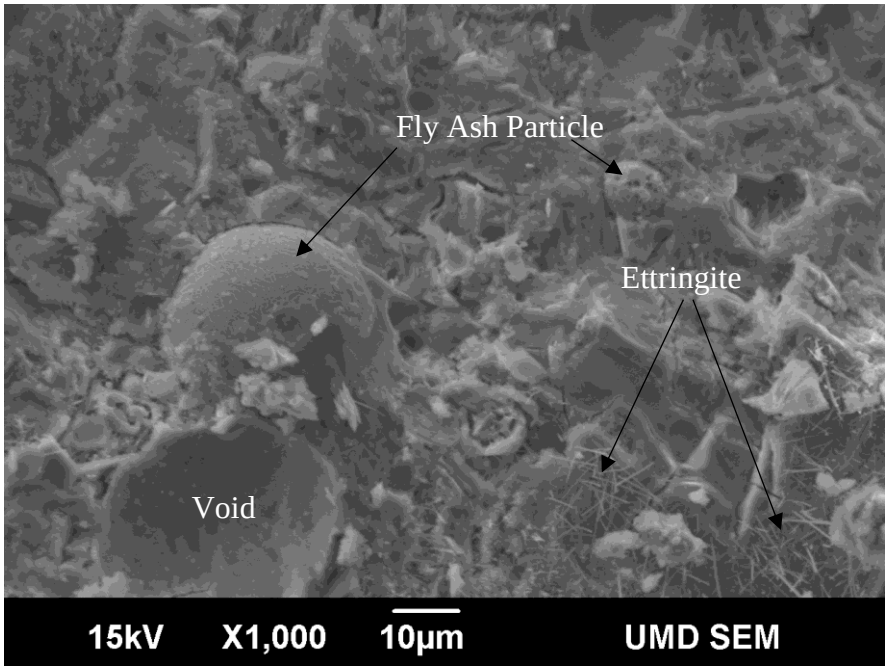


Figure 4.36. SEI for PC sample at 15kV and x1000.

4.3.6.1.2 Class F Fly Ash (FA2) Sample

Figure 4.37 shows the fractured surface for the fly ash sample at 20% in two different areas. The microstructure of this sample shows partially dissolved and fully undissolved

fly ash particles, which is common to see. The formation of ettringite this late indicates that re-crystallization occurred due to a change in composition or moisture, possibly from the curing chamber, and was able to from by dissolving small monosulfate crystals. Since no expansion was observed, this formation of ettringite does not harm the sample. Had expansion occurred with the formation of ettringite, large cracks at great amounts would have been observed and the compressive strength values would have diminished.



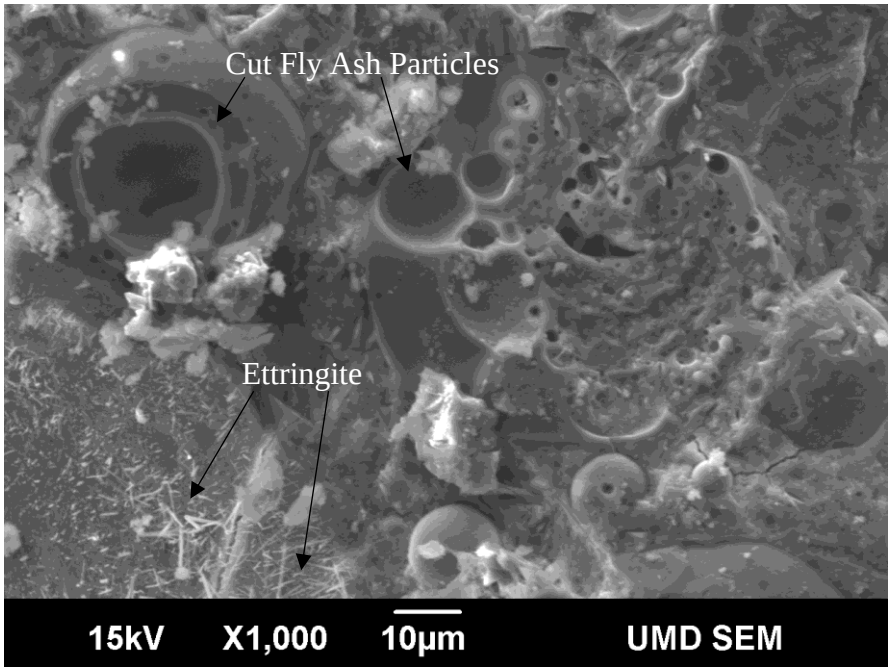


Figure 4.37. SEI for Class F fly ash at 20% replacement at 15kV and x1000.

4.3.6.1.3 Sample Q

Figure 4.38 shows the microstructure of a fractured surface of sample Q at 20% at two different areas. The structure looked compacted with little to no ettringite, cracking, and it showed some unhydrated glass particles. This well-formed structure indicates why this glass sample performed well during compressive strength testing.

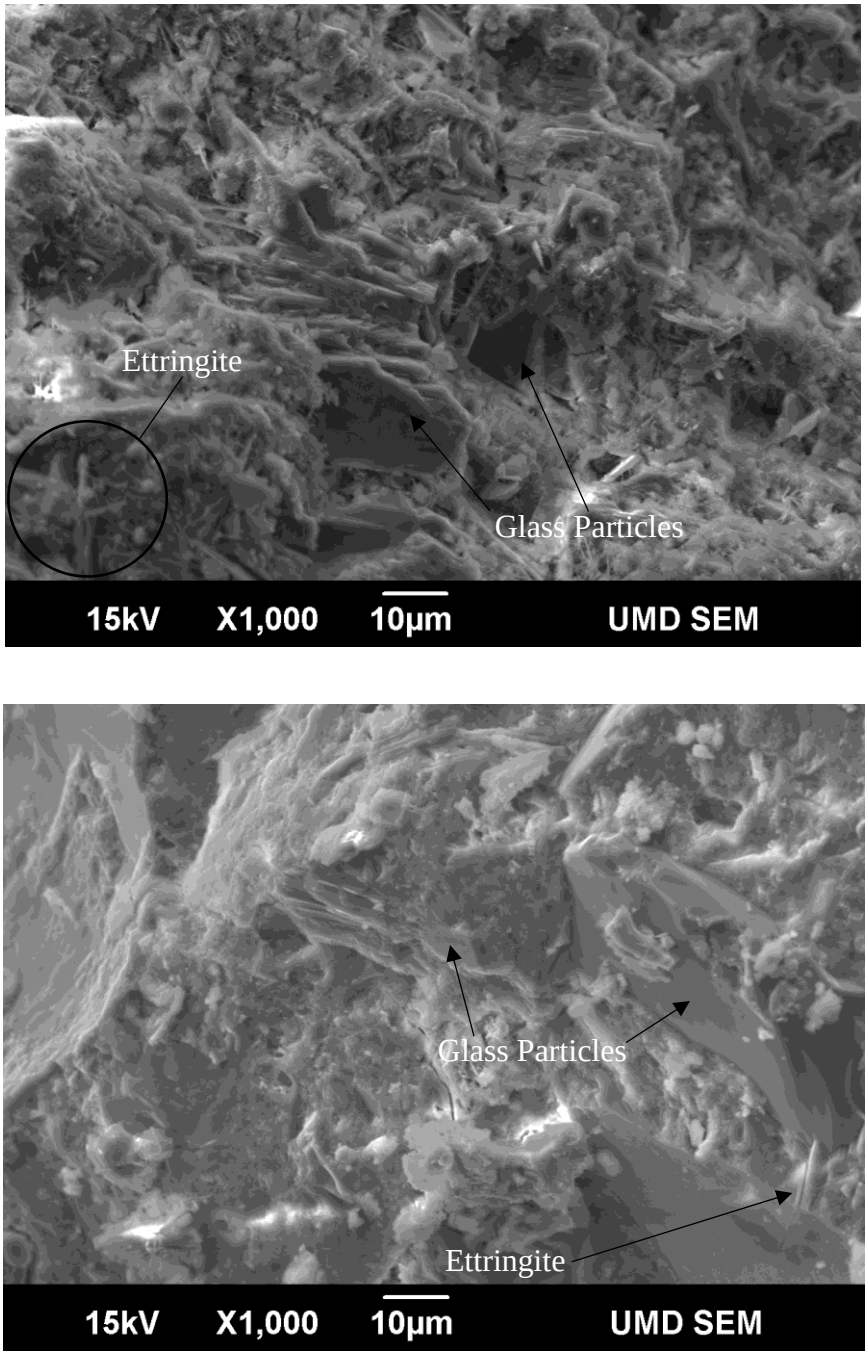


Figure 4.38. SEI for sample Q at 20% replacement at 15kV and x1000.

4.3.6.1.4 Sample S

Figure 4.39 shows the microstructure of two different locations on the fractured surface of sample S at 20%. The microstructure also shows cracks of various sizes formed around glass particles and a micro structure that is not as compact as other samples. This could indicate why sample S had the lower compressive strength out of all the samples examined. Granted, the microstructure observed in these images are not the worst, but with a large strength increase from 90 days to 6 months, a positive change in its structure had to occur. Out of all the fractured glass sample surfaces, this glass seemed to have a large amount of glass particles not fully reacted. That could play into the final compressive strength results. It is also important to notice that as time went on during the curing process, some expansion was observed making the sample less dense.

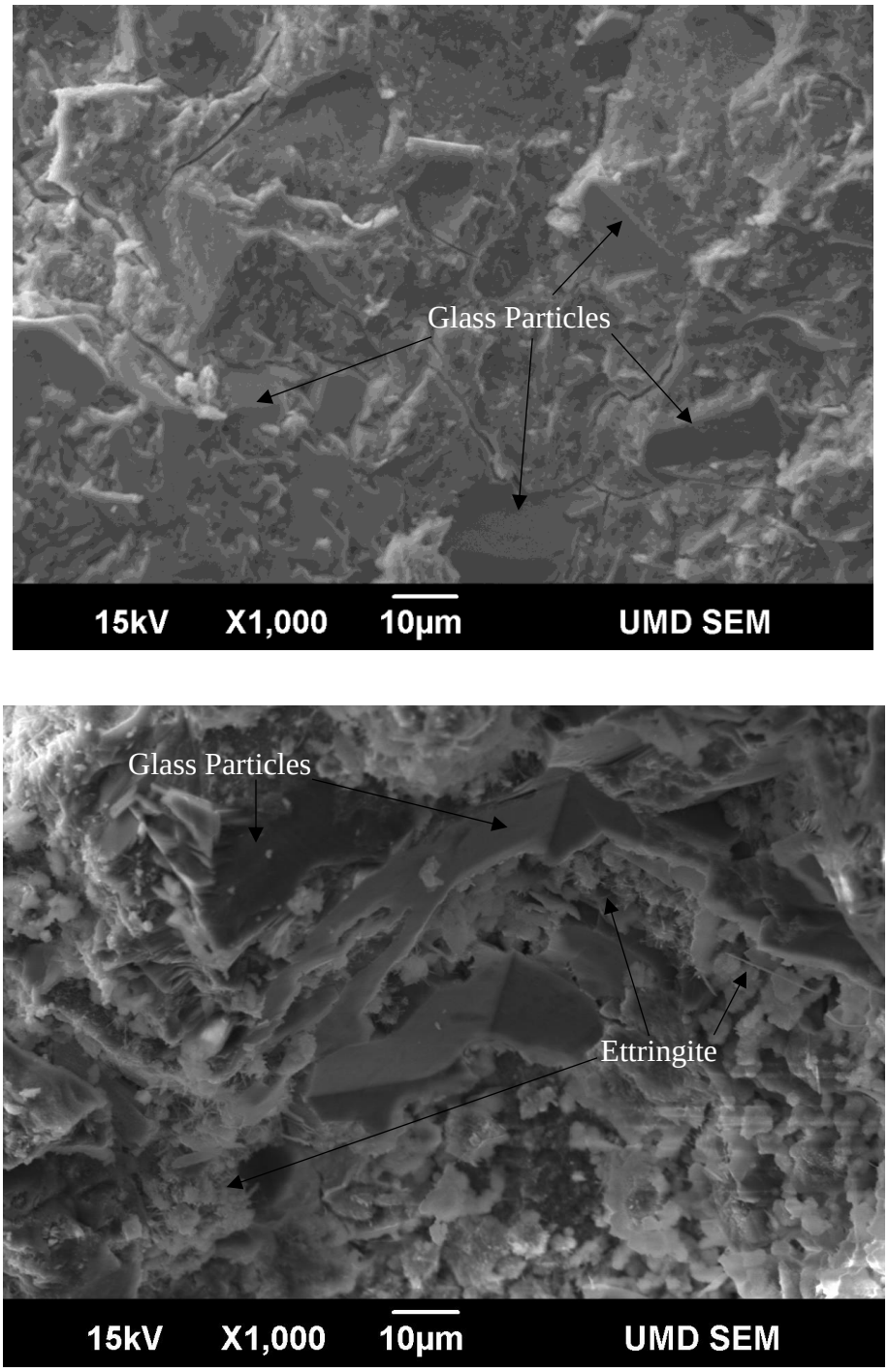


Figure 4.39. SEI for sample S at 20% replacement at 15kV and x1000.

4.3.6.1.5 Sample T

Figure 4.40 shows the microstructure of a fractured sample T at 20% surface at two different locations. The microstructure for sample T shows a few small glass particles, and a micro-structure that is well formed, but not as formed as sample Q. Sample T had one of the highest compressive strengths for a dirty soda-lime container glass. This indicates that even with any contaminants that could have been on the glass, it formed a compacted structure and gave high compressive strength values. No change in size was observed throughout the curing process.

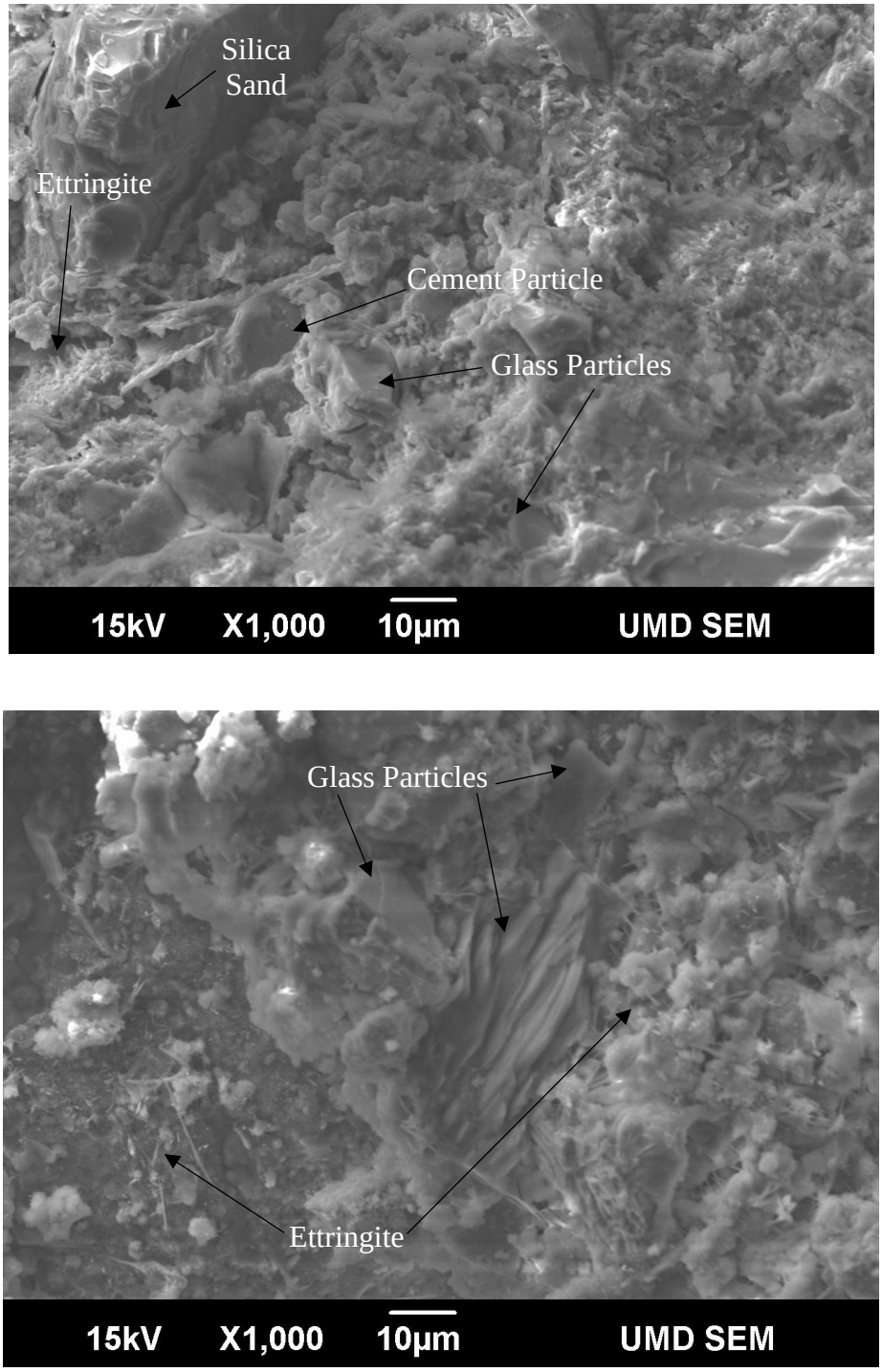


Figure 4.40. SEI for sample T at 20% replacement at 15kV and x1000.

4.3.6.2 Backscattered Imaging and Energy-Dispersive Spectroscopy

Polished surfaces were used to take the Backscattered Imaging (BSE) images, which also allowed Energy-Dispersive Spectroscopy (EDS) to be performed. EDS can be performed on a fractured surface, but due to the elevations found on a fractured surface the compositional results won't be as reliable. Therefore, EDS was only performed on polished surfaces. A flat surface will give more reliable and accurate composition results. To help analyze these results and images, the book, "Scanning Electron Microscopy of Cement and Concrete" (Winter, 2012) was used. This book provided peaks to look for in the EDS data, along with the brightness of a hydration product from a BSE image. All the hard data and observed locations analyzed for each image can be found in Appendix A.

4.3.6.2.1 Portland Cement (PC) Sample

Figure 4.41 shows the polished microstructural surface for the control sample at two different locations. A dense microstructure often indicates a stronger, more durable concrete. There are some unhydrated portland cement particles, silica sand, and an ITZ visible.

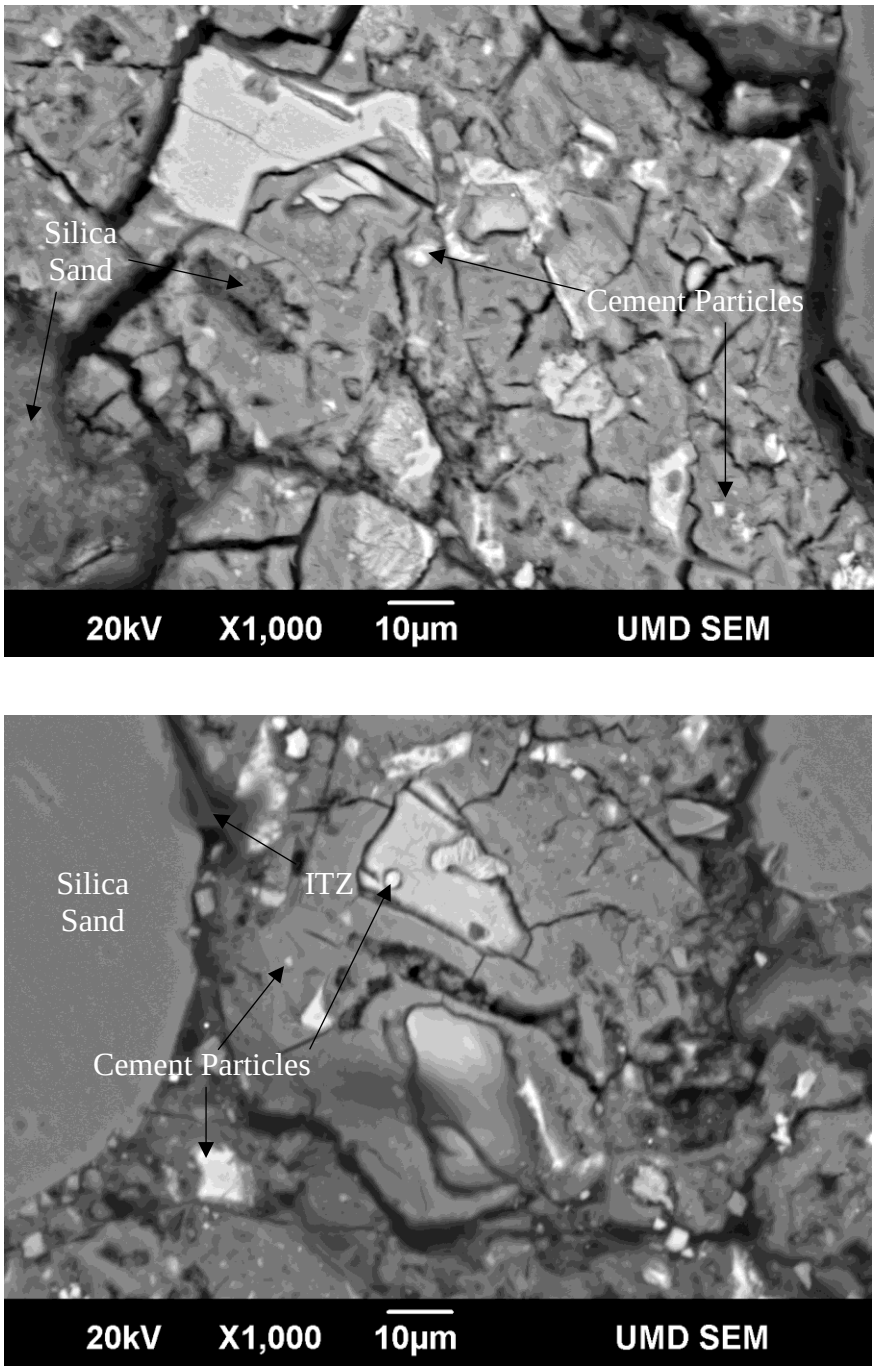


Figure 4.41. BSE for PC sample at 20kV and x1000.

4.3.6.2.2 Class F Fly Ash (FA2) Sample

Figure 4.42 shows the microstructure of a polished fly ash sample at two different locations. As is common with any fly ash sample, fly ash particles are shown at various sizes. There was a lot of hydration products formed between the sand particles, making for a dense structure.

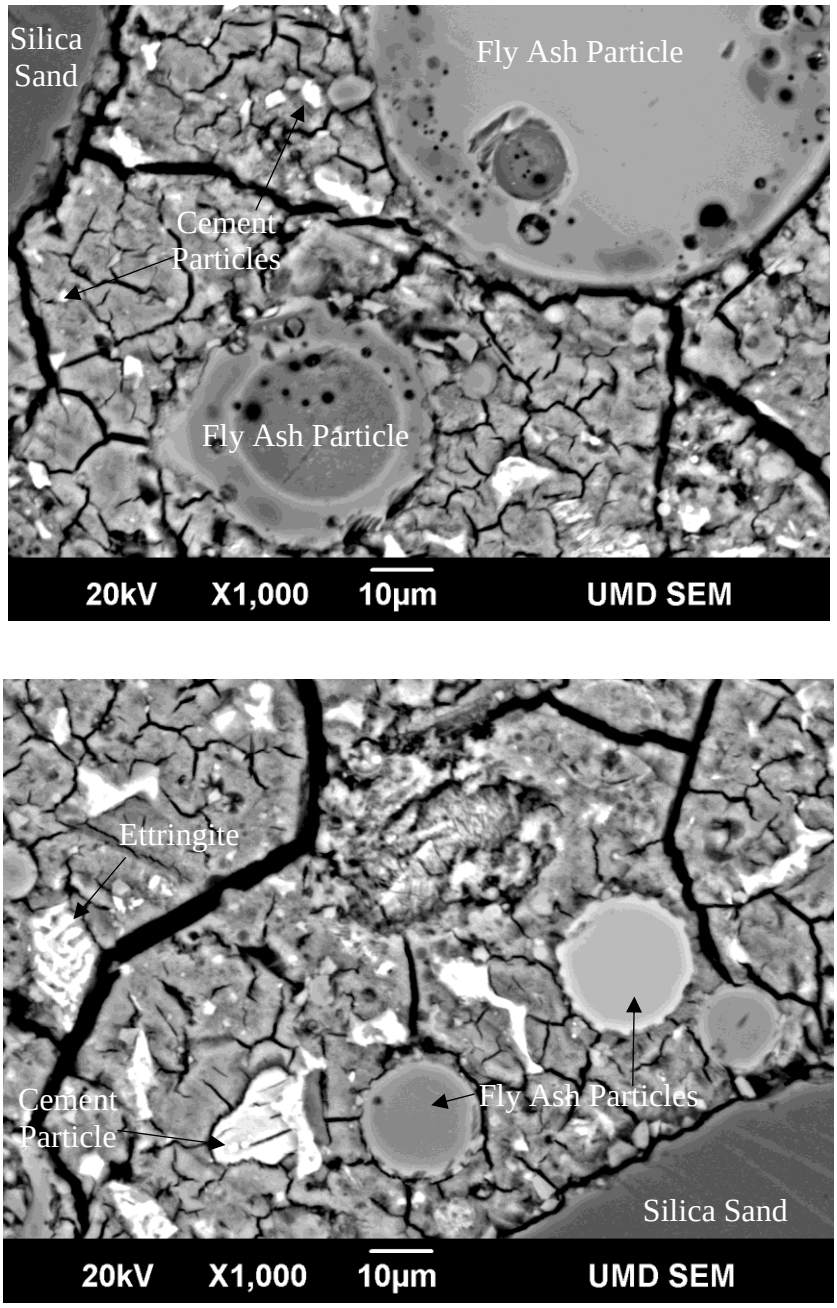
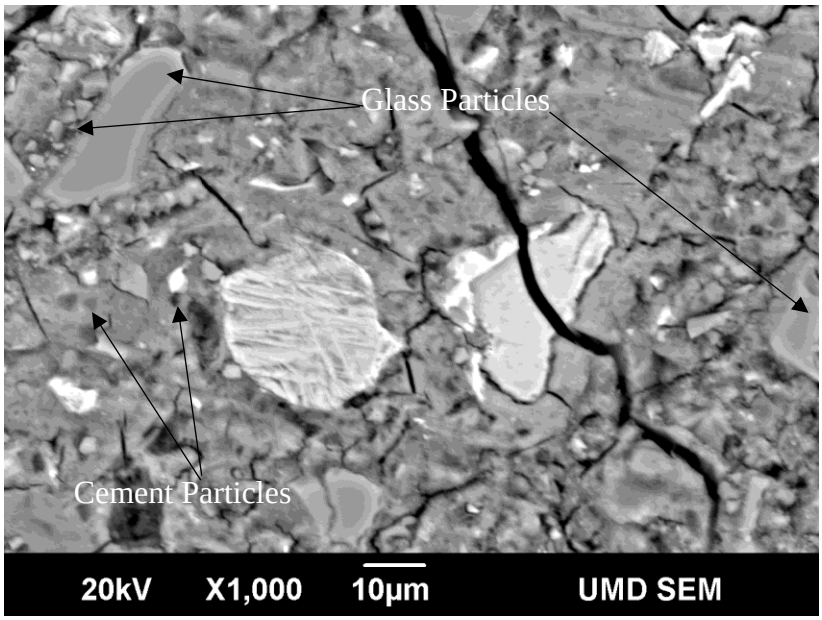


Figure 4.42. BSE for Class F fly ash sample at 20% replacement at 20kV and x1000.

4.3.6.2.3 Sample Q

Figure 4.43 contains two locations of sample Q's microstructure of a polished surface. This sample showed various sizes of glass particles along with a small amount of little portland cement particles. The dense microstructure could indicate why sample Q had a large compressive strength even from day 1. It is important to note how these unidentified structures look in sample Q when comparing them to samples S and T. Sample Q had higher compressive strength results than samples S and T.



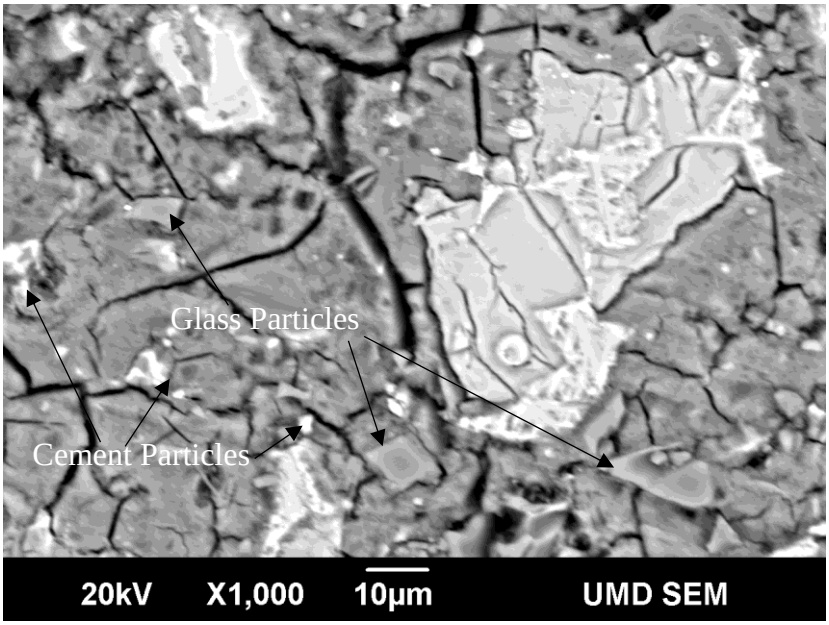


Figure 4.43. BSE for sample Q at 20% replacement at 20kV and x1000.

4.3.6.2.4 Sample S

Figure 4.44 shows the polished microstructural surface for sample S at two different locations. There was also a very bright spot on one of the images. After running EDS on that one spot, it was observed to be fully made of iron. This could indicate that a metal contaminant was on the glass sample even though this glass went through the MRF cleaning process. There could be more contaminants, besides soap, within the S samples that could have also played in weak compressive strength values. Small portland cement particles and some large unreacted glass particles were also observed. The unidentified structures in sample S look different from the unidentified structures in sample Q. This could indicate why sample S had compressive strength values less than sample Q.

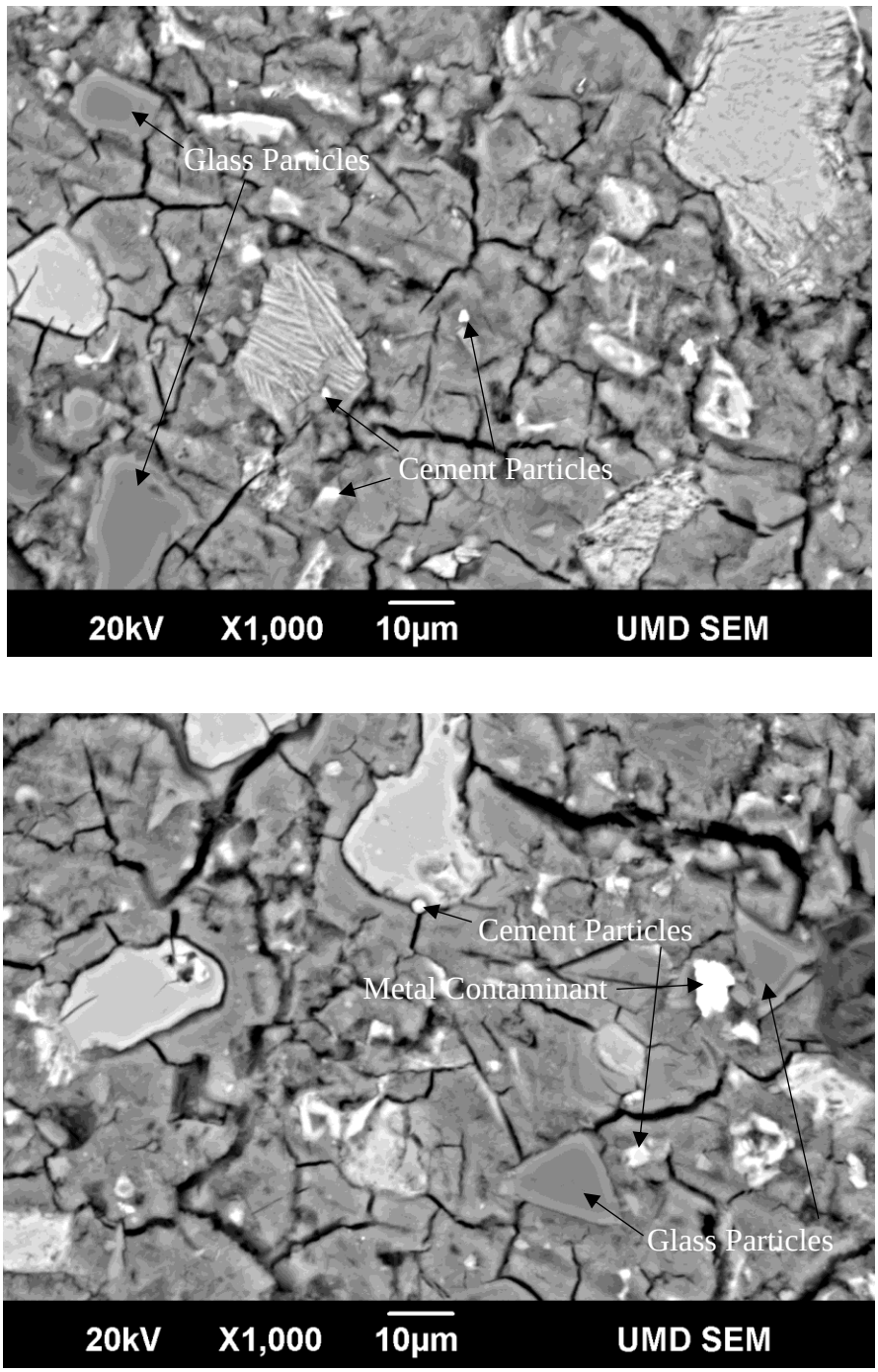
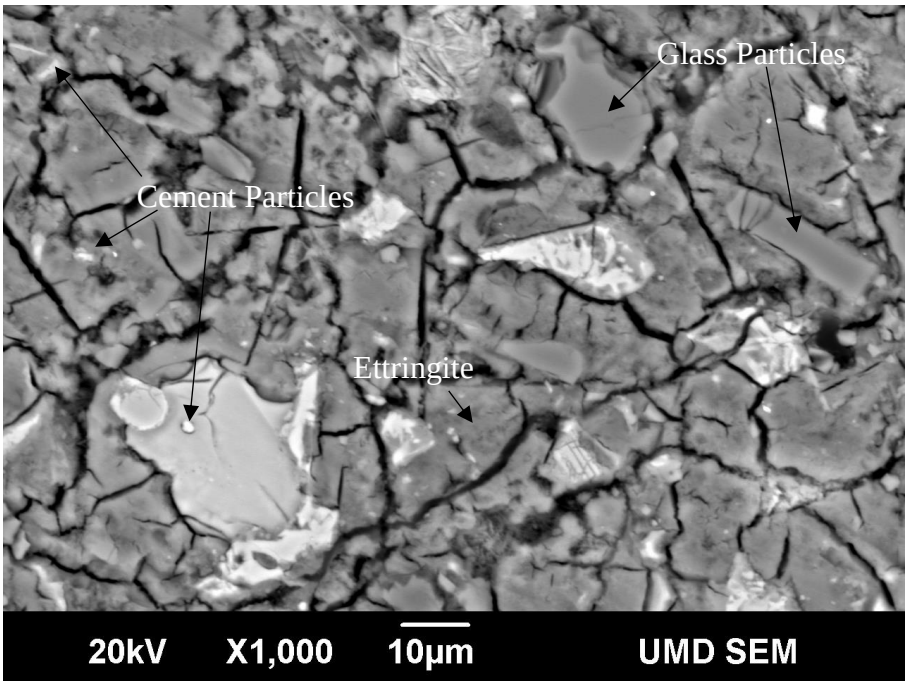


Figure 4.44. BSE for sample S at 20% replacement at 20kV and x1000.

4.3.6.2.5 Sample T

Figure 4.45 contains the polished microstructure of sample T at two different locations. Unhydrated portland cement particles and unreacted glass particles were also observed. The unidentified structures in sample T resemble a combination of the structures noticed in samples Q and S. This could indicate why sample T had compressive strength values between samples Q and S.



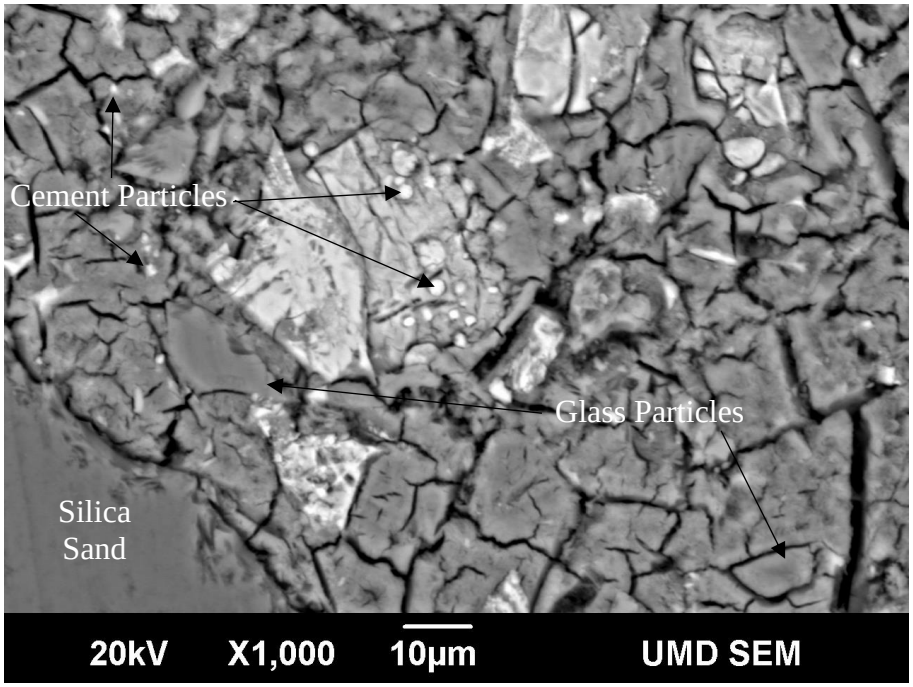


Figure 4.45. BSE for sample T at 20% replacement at 20kV and x1000.

5 Conclusions

The purpose of this research was to investigate how the composition and replacement level of ground waste glass affects the compressive strength and hardened air void system of portland cement mortars when it is used as a pozzolan. This is important since not every glass is the same and may perform differently. The following sections directly answer the initial research questions.

5.1 How does the glass composition and replacement level affect the early and later age compressive strength of portland cement based mortars when used as a pozzolan?

5.1.1 Glass Composition

Glass composition did play a role in determining the compressive strength of the samples. The composition of any pozzolan used in a concrete mixture design is important to know and understand since that determines how that pozzolan will perform. Not all glass is the same and it should be classified into different types based on its composition. The glass in this research was classified into the following types based upon comparing compositions found in the literature: soda-lime container, soda-lime plate, soda-lime container and plate, aluminosilicate and glass ceramic, E-glass, TV and CRT panel (barium) and soda-lime container, and phosphate and soda-lime container glass. Examining different glass types showed some difference in compressive strength results. It was observed that aluminosilicate glass and glass ceramic had the lowest compressive strength results and experienced a strength drop during the testing process making it a less reliable glass type. E-glass did very well compared to the other glass types from the

tests performed. One reason for E-glass performing well is believed to be from it having a higher CaO amount compared to the other glass types. Having a high CaO amount allowed for more C-S-H and C-A-S-H gel to form causing a strong and durable mixture. E-glass would be a good glass type to investigate further, but since it is not a common glass type it would not make for a feasible concrete mixture. Soda-lime glass, container, plate, or a mix of the two, experienced large enough compressive strength results that showed this glass type as being reliable since soda-lime glass had the largest sample size out of all the glass types tested.

Glass that was classified as a similar glass type experienced slight variation between each other in compressive strength, hardened air-void, and microscopy tests. A good example of this slight variation was observed in sample S and sample T. Both glass samples are classified as a soda-lime container glass with almost identical compositions but very different compressive strength, hardened air void, and microscopy results. One significant difference between these two is sample S went through the cleaning process of the Material Recycling Facility (MRF), while sample T never went through any process and was considered dirty since it was mixed with trash and other recyclables. One possible reason why this happened ultimately came down to contaminants. One of the common contaminants to have on glass powder is soap, because it can negatively affect the bonding during the hydration phases and create unwanted air voids. Another reason for this difference between sample S and T could be something that was added during the cleaning process that negatively affected sample S. Soda-lime container glass had the largest sample size and experienced a compressive strength difference between the

largest and smallest results of 568psi on 1 day to 1568psi on 6 months. This difference showed that there was a small compressive strength variation in soda-lime container glasses.

There was no clear correlation found with the compressive strength data that stated a glass with given weight percent of a specific oxide would yield a specific compressive strength by 28 days. What can be found from the data is what oxides are needed to classify a glass as a certain glass type and which glass type(s) performed better than others. These two things are significant for further research into glass as a pozzolan. With the compressive strength data and XRF data to help classify a glass as a certain glass type, a large beginning step was made in glass pozzolan research. The other thing that helped further research into glass as a pozzolan is an optimal replacement level to use in future testing.

5.1.2 Glass Replacement Level

Glass replacement level did play a role in determining the compressive strength of the samples. Along with examining the composition of a glass powder, it was essential to investigate what common portland cement replacement amounts, 20 or 30%, with glass powder would produce the best results. Composition and replacement level tend to go hand in hand since a pozzolan's composition plays a key role in how much portland cement can be replaced. As long as there are still sufficient amounts of silica, SiO_2, and/or alumina, Al_2O_3 in the pozzolan, a pozzolan with a high amount of calcia, CaO, has

a better chance to replace more portland cement than a pozzolan with low CaO since CaO is essential in forming C-S-H to help strengthen the hardened structure of the mixture. This research showed that there was an important difference in compressive strength results between the 20 and 30% replacement levels. For the most part, all glass types, excluding E-glass, on each break day performed better at 20% than 30%. The only glass that significantly performed better at 30% replacement level was E-glass and that was more than likely due to the high amount of CaO in its composition. It was the only glass type with a CaO amount above 20%, while the other glasses had a CaO amount less than 12%. By replacing too much portland cement with a glass powder that has low amounts of CaO, there would not be enough calcia to help form proper amounts of C-S-H causing a weak sample instead of a strong, durable, and dense sample.

At 20% replacement levels, higher compressive strength values with a SAI of 75% or higher from 7 days and beyond was observed compared to their 30% replacement level counter parts. For the most part, samples at a 30% replacement level didn't have a SAI value above 75% until 28 days but they were not that far above 75%. In comparison, 20% replacement levels, for the most part, had SAI values above 75% at 7 days and had SAI values around 80% or more by 28 days. After 28 days, only one glass type at 20% replacement, TV/CRT panel and soda-lime container glass or glass H, did not pass the 75% SAI requirement at 56 days. This sample had a strength loss between 28-90 days, which could have been due to the SiO_2+Al_2O_3+Fe_2O_3 amount being less than 70% (ASTM Standard C618, 2015). Even though SAI requirement is only looked at from 7 to

28 days, it is important that later day strengths also meet this requirement to ensure that hydration phases and products are staying strong and not getting weak.

By looking at each figure in the early and later strength sections and examining the data points as a whole and not as individual samples, some connections were able to be made, but nothing stood out as a large contributing factor.

For early strength at both replacement levels, there were some noticeable linear relationships on the CaO and sum of the oxides graphs and no noticeable relationships on the w/cm and $Na_2O_{(eq)}$ graphs. By understanding how much glass powder and portland cement make up each sample, there is a chance that CaO and $Na_2O_{(eq)}$ would affect 30% replacement level more than 20% replacement level, while SiO_2+Al_2O_3+Fe_2O_3 amount and w/cm ratio would affect 20% replacement level more than 30% replacement level due to hydration products forming in the early curing stages.

The SiO_2+Al_2O_3+Fe_2O_3 amount and w/cm ratio will affect a 20% replacement level glass powder mixture due to early hydration phases and products trying to form which can affect how good of a bond will form in the structure. $Na_2O_{(eq)}$ and CaO amounts would possibly affect early strength due to glass powders having a high amount of alkalis as compared to other pozzolans. As stated before, CaO amount is important in a mixture due to it helping form hydration phases and products. With less portland cement being involved in a 30% replacement level mixture, these hydration phases and products depend significantly on the glass powder to provide enough CaO which was an issue

since CaO was low for most glass types. $SiO_2+Al_2O_3+Fe_2O_3$ amount is not as important with a 30% replacement level due to an ample amount of available silica and alumina ready to form hydration phases and products.

For 20% replacement level, all glass types except two, TV/CRT panel and soda-lime container and aluminosilicate and glass ceramic, had a SAI of at least 75% from 7 to 28 days with some in the high 80's, 90's, and low 100's. For 30% replacement level, only the E-Glass had a SAI of at least 75% by 7 days. By 28 days, soda-lime container and plate glass, soda-lime plate glass, phosphate and soda-lime container glass, and E-Glass had a SAI of at least 75%. From 7 to 28 days, only two samples, Q and T, had a SAI of at least 80%.

For later strength at a 20% replacement level, there was some noticeable linear relationships on the CaO and sum of the oxides graphs and no noticeable relationships on the w/cm and $Na_2O_{(eq)}$ graphs. At 30% replacement level, there was some noticeable linear relationships on the w/cm ratio, CaO, and sum of the oxides graphs and no noticeable relationships on the $Na_2O_{(eq)}$ graph. By understanding how much glass powder and portland cement make up each sample, there is a chance that CaO and $Na_2O_{(eq)}$ would affect both replacement levels, but at different rates, more than they do in early curing stages. By later curing ages, like 90 days, hydration bonds have already formed and the issues become anything that can affect and break down these bonds. Alkalis and any water that has not reacted yet become the main issues in the hardened structure. The

alkalis will want to react with any monosulfates causing large ettringite to form which will cause expansion and cracks. The water will want to react with any CH it comes across which will cause more entrapped air-voids to form. Both of these reactions will cause the sample to become weak and less durable. Besides from CaO becoming CH, any unreacted CaO will want to form with more available SiO_2 and Al_2O_3 to form more bonds. Depending on if the CaO has reacted to form CH or it has not reacted yet can determine how much CaO amount becomes an issue to the hardened structure.

Excluding the glass type TV/CRT panel and soda-lime container glass, all the glass types at 20% replacement had a SAI of at least 80% from 56 days to 6 months with some in the high 90's and low 100's. An SAI over 100 indicates those samples were stronger than the portland cement control at that break day. For 30% replacement level, E-Glass, soda-lime plate glass, and phosphate and soda-lime container glass were the only three to have a SAI of at least 82% with the rest of the samples barely reaching 80% SAI.

5.2 How does glass composition and processing parameters affect the hardened air-void structure of portland cement based mortars when used as a pozzolan?

The difference in the hardened air-void results indicates that glass composition and processing parameters did play a role in the microstructure of the mortar. As stated before, the hypotheses for Phase I and Phase II was that the mixtures with the largest SiO_2+Al_2O_3+Fe_2O_3 percentage would result in larger strength values due to more C-S-H or C-A-S-H forming from the pozzolanic reaction and the samples with a weak compressive strength and poor air-void structure could be due to having a high level of

bad contaminants. The hardened air-void results showed that the cleaner and better processed the glass powder was, the higher the average air content was. The dirtier and less processed the glass powder was, the higher the average paste content, average void frequency, and the average specific surface was and the smaller the spacing factor was. There is a correlation between w/cm ratio and spacing factor. It was observed that the higher the w/cm ratio was, the higher the average spacing factor was for the glass powder samples. Between the three glass samples tested, samples Q, S, and T, processing parameters seemed to play a large role. These parameters can decide the level of contaminants and affect the hardened structure formation and w/cm ratio. This can be said due to S and T being similar in composition but different in processing parameters; S was clean, and T was dirty.

5.3 How does glass composition and processing parameters affect the microstructure in portland cement based mortars when used as a pozzolan?

By looking at each microstructure image, it was determined that glass composition and processing parameters did play a role in the final microstructure of the mortar.

Processing parameters is another way of indicating how clean or dirty the glass was or if any chemicals were added to the glass powder to affect its properties. Out of the samples that had their microstructure examined, glass S went through the cleaning process of a MRF, glass T was dirty and essentially from the trash and mixed recyclables, and glass Q kept separate from all other trash and recyclables. Glasses S and T show that processing parameters can play an important role in the hardened structure due to these two glasses

having almost identical compositions indicating that they should see similar results in mixing and testing, yet they saw very different results. S, as compared to T, had a lower w/cm ratio, compressive strength values, and hardened structure. The difference in the cleaning process could have affected the hardened structure significantly, which affected the air-void and compressive strength results. Sample Q had the best formed hardened structure followed by samples T and S. This was observed by the well-formed and compacted C-S-H gel in both the fractured and polished surfaces of sample Q.

5.4 Recommendations for Future Work

This research is just the beginning of helping glass powder become a commercially used pozzolan in concrete mixtures. Just like any other pozzolan ever used in concrete, there are a great number of tests that need to be ran in order to truly understand the effects of including it in concrete. This research showed that certain glass types are better than others and it is important to know how the facility providing the glass receives the glass and how they clean and treat it. To help build into further research, it is recommended to look at soda-lime container and soda-lime plate glasses since they are the most common to find at MRFs and overall performed the best in each test.

The first recommendation for future research on glass powder as a pozzolan would be to perform an in-depth examination of the contaminants on glass samples to see how they affect the microstructure formation, compressive strength, and durability results. As stated before, contaminants can influence the performance of a glass powder due to it

affecting the sample's structure from bonding properly in the hydration process; some surface contaminants include soap, food, and other trash. It was observed in the BSE microstructure image for sample S that a possible metal contaminant was found, which possibly affected its compressive strength values. Some other possible future projects include taking the information gathered from this research and determining if adding another pozzolan, like fly ash, would enhance the performance of the glass mixtures. This is an addition of another pozzolan, not a replacement. Running freeze-thaw testing on the glasses that performed well with compressive strength to see how durable they are and compare those to hardened air-void results. Running more hardened air-void and microscopy tests on a larger variety of glass powder samples to better correlate what affect their systems.

Utilizing glass powder as a pozzolan and replacing a portion of portland cement is a good step to lowing portland cement production emissions and lowering the amount of glass that ends up in the ground. Glass powder can perform just as well or even better than other pozzolans and further research should heavily be considered on it so that it can be approved as a common pozzolan to use in construction projects.

6 Bibliography

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7 Appendix A

7.1 Microanalysis Results

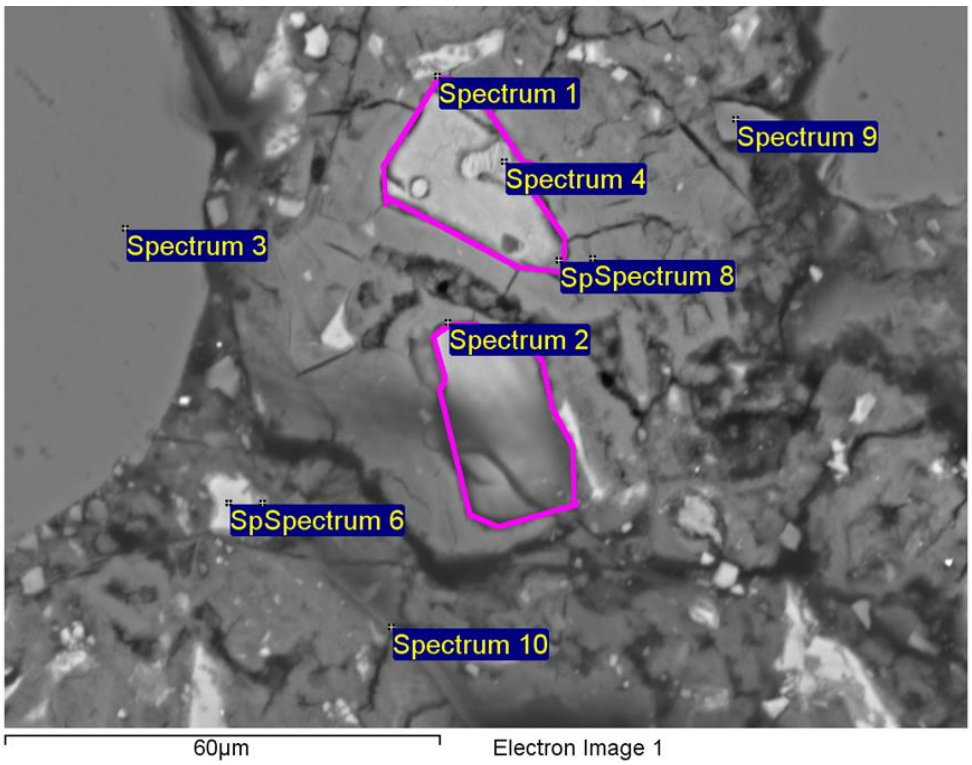

Figure 7.1. BSE of polished portland cement section with selected locations for EDS.

Table 7.1. EDS values of selected locations from Figure 7.1.

	Composition (% by mass)										
Spectrum	**SiO_2**	**CaO**	**Na_2O**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**SO_3**	**K_2O**	**TiO_2**	**P_2O_5**	**Mn_2O_3**
1	30.65	61.57	1.08	1.92	1.33	1.54	-	1.91	-	-	-
2	28.20	62.48	0.48	3.45	2.89	1.70	-	0.79	-	-	-
3	100.00	-	-	-	-	-	-	-	-	-	-
4	27.60	59.53	1.12	3.92	3.10	1.52	-	2.81	0.39	-	-
5	27.36	52.80	1.30	3.11	2.41	0.84	5.56	6.61	-	-	-
6	35.87	42.55	2.01	3.42	1.20	2.38	5.51	7.06	-	-	-
7	39.65	51.00	0.67	1.96	1.31	2.95	-	2.45	-	-	-
8	34.93	52.38	1.17	2.02	1.23	1.71	2.99	3.57	-	-	-
9	67.52	21.46	0.74	2.17	0.93	0.98	3.99	2.21	-	-	-
10	34.99	47.63	1.10	7.34	1.56	2.22	1.92	3.25	-	-	-

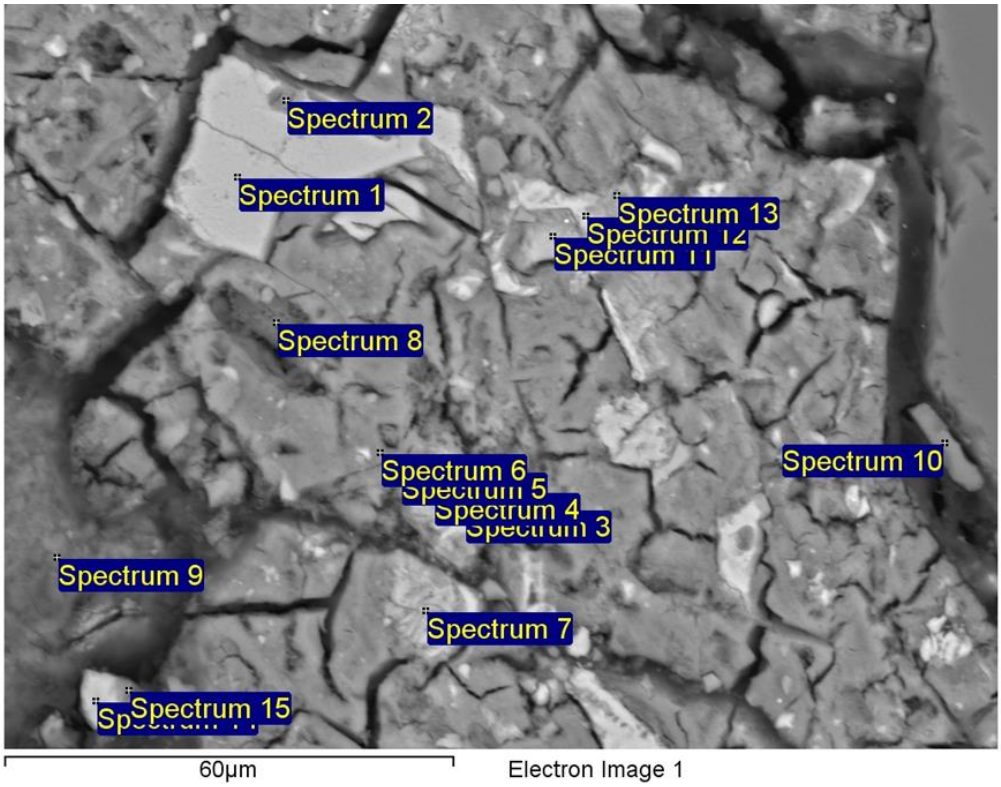

Figure 7.2. BSE of polished portland cement section with selected locations for EDS.

Table 7.2. EDS values of selected locations from Figure 7.2.

	Composition (% by mass)										
Spectrum	SiO_2	CaO	Na_2O	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	TiO_2	P_2O_5	Mn_2O_3
1	6.18	50.63	-	22.49	16.09	3.73	-	0.43	0.46	-	-
2	8.95	51.11	-	21.77	13.40	2.31	2.46	-	-	-	-
3	4.61	47.63	-	23.18	21.38	2.78	-	-	0.42	-	-
4	32.53	63.30	-	1.66	0.99	0.41	0.82	0.29	-	-	-
5	30.82	58.96	-	3.38	1.77	1.16	3.91	-	-	-	-
6	39.25	52.24	-	2.70	1.44	2.35	2.02	-	-	-	-
7	34.74	60.76	-	1.74	1.17	0.40	0.90	0.30	-	-	-
8	6.61	89.90	-	0.96	0.63	0.35	1.55	-	-	-	-
9	97.64	2.36	-	-	-	-	-	-	-	-	-
10	99.69	0.31	-	-	-	-	-	-	-	-	-
11	24.45	72.82	-	1.00	0.89	0.84	-	-	-	-	-
12	5.67	48.45	-	23.88	17.59	3.64	-	0.20	0.57	-	-
13	18.13	51.98	-	11.92	11.29	3.20	3.28	0.20	-	-	-
14	5.22	48.17	-	23.98	17.35	3.85	0.00	0.97	0.46	-	-
15	19.05	44.32	-	14.26	12.62	3.56	5.48	0.29	0.42	-	-

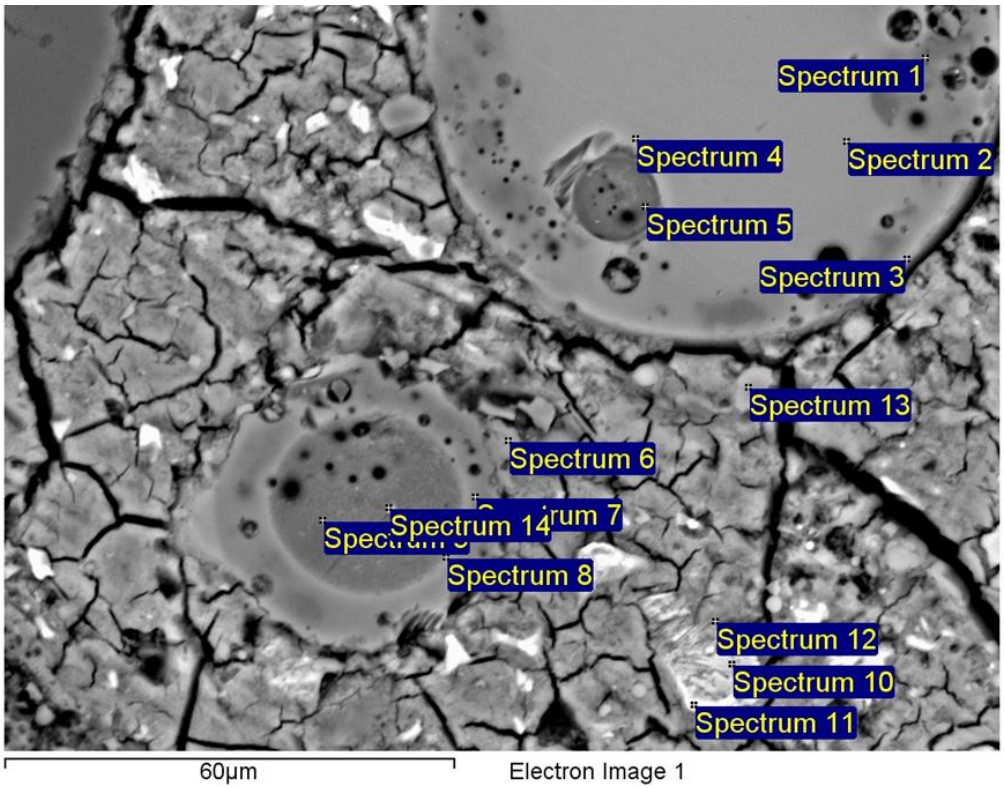

Figure 7.3. BSE of polished FA2@20% section with selected locations for EDS.

Table 7.3. EDS values of selected locations from Figure 7.3.

	Composition (% by mass)										
Spectrum	**SiO_2**	**CaO**	**Na_2O**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**SO_3**	**K_2O**	**TiO_2**	**P_2O_5**	**Mn_2O_3**
1	80.95	2.28	0.61	9.56	1.69	0.86	-	3.70	0.36	-	-
2	51.35	17.47	0.36	17.24	5.48	6.53	-	1.15	0.41	-	-
3	53.44	15.03	1.43	14.69	6.09	2.17	0.75	5.18	1.23	-	-
4	52.65	16.62	0.51	17.78	4.68	5.63	-	1.55	0.59	-	-
5	48.42	23.86	0.47	11.67	8.26	1.80	-	4.85	0.67	-	-
6	54.31	14.73	2.65	14.73	4.02	4.27	0.42	4.58	0.29	-	-
7	73.27	2.27	1.12	15.81	1.36	1.39	-	4.35	0.43	-	-
8	62.45	4.46	1.31	21.79	2.57	3.27	-	3.52	0.64	-	-
9	69.84	2.84	1.15	17.50	1.98	2.01	-	3.97	0.72	-	-
10	34.05	60.68	0.00	1.76	1.01	0.88	0.92	0.70	-	-	-
11	13.96	48.51	0.71	19.47	13.09	2.49	0.81	0.96	-	-	-
12	33.77	51.92	1.31	4.11	1.73	0.89	3.54	2.73	-	-	-
13	58.35	11.24	1.63	16.91	4.01	3.77	-	3.65	0.44	-	-
14	74.56	2.93	0.96	14.22	1.73	1.69	-	3.37	0.54	-	-

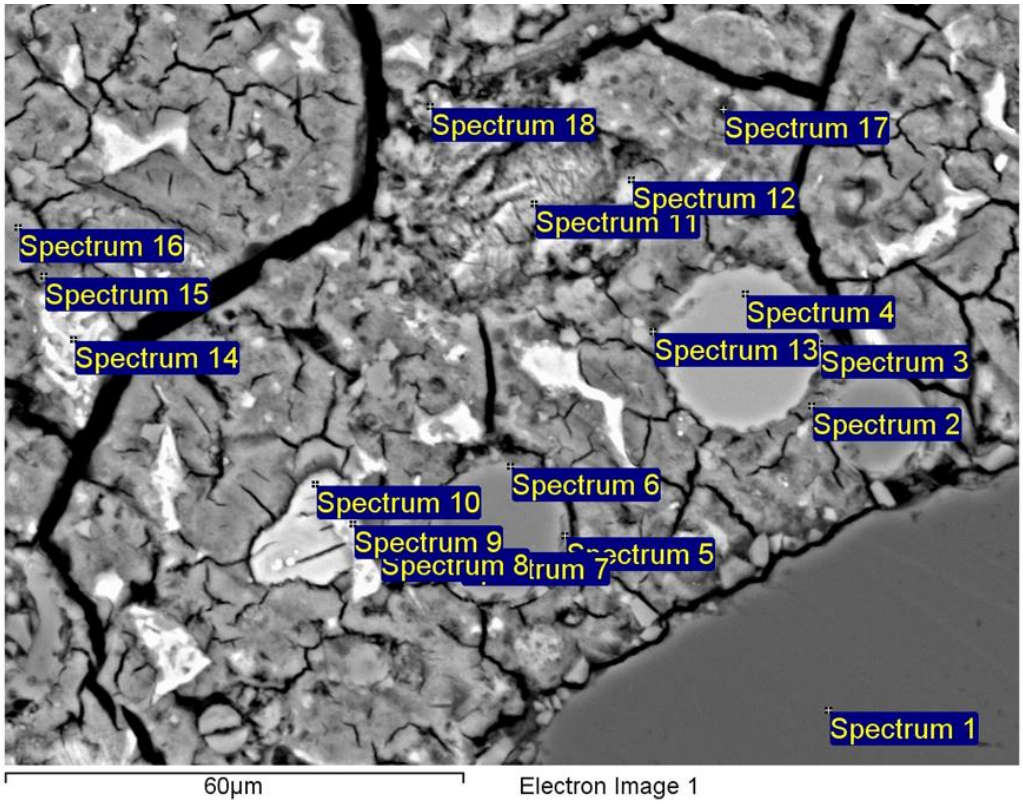

Figure 7.4. BSE of polished FA2@20% section with selected locations for EDS.

Table 7.4. EDS values of selected locations from Figure 7.4.

	Composition (% by mass)										
Spectrum	SiO_2	CaO	Na_2O	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	TiO_2	P_2O_5	Mn_2O_3
1	100.00	-	-	-	-	-	-	-	-	-	-
2	33.86	43.19	1.95	5.86	4.05	2.04	4.34	4.26	0.45	-	-
3	33.55	32.82	2.46	8.86	6.16	10.53	1.14	4.05	0.43	-	-
4	42.94	30.89	-	11.90	5.10	8.84	-	-	0.33	-	-
5	55.43	10.53	3.41	16.41	4.70	4.38	0.47	4.25	0.40	-	-
6	57.67	8.68	3.81	17.13	3.94	4.43	-	4.00	0.33	-	-
7	63.63	4.64	2.77	17.54	3.51	3.15	-	4.34	0.42	-	-
8	38.66	50.93	1.08	4.06	1.78	1.85	-	1.65	-	-	-
9	18.12	46.78	-	15.39	15.02	3.64	0.54	0.51	-	-	-
10	31.39	61.63	0.40	3.13	1.70	1.22	-	0.52	-	-	-
11	8.79	84.13	1.00	1.15	0.50	0.38	2.89	1.16	-	-	-
12	28.50	47.79	3.43	5.34	1.57	1.14	7.31	4.92	-	-	-
13	36.16	45.06	0.65	5.77	4.13	3.54	2.81	1.51	0.37	-	-
14	5.36	53.44	0.43	25.11	12.73	2.23	-	0.70	-	-	-
15	24.02	43.82	2.90	9.70	4.34	2.44	6.64	6.14	-	-	-
16	18.74	40.21	-	15.29	10.12	10.54	2.48	0.48	1.04	1.09	-
17	28.72	44.09	1.68	6.62	4.78	3.54	4.84	4.88	0.83	-	-
18	24.58	39.63	2.39	8.81	6.68	10.61	1.84	4.73	0.73	-	-

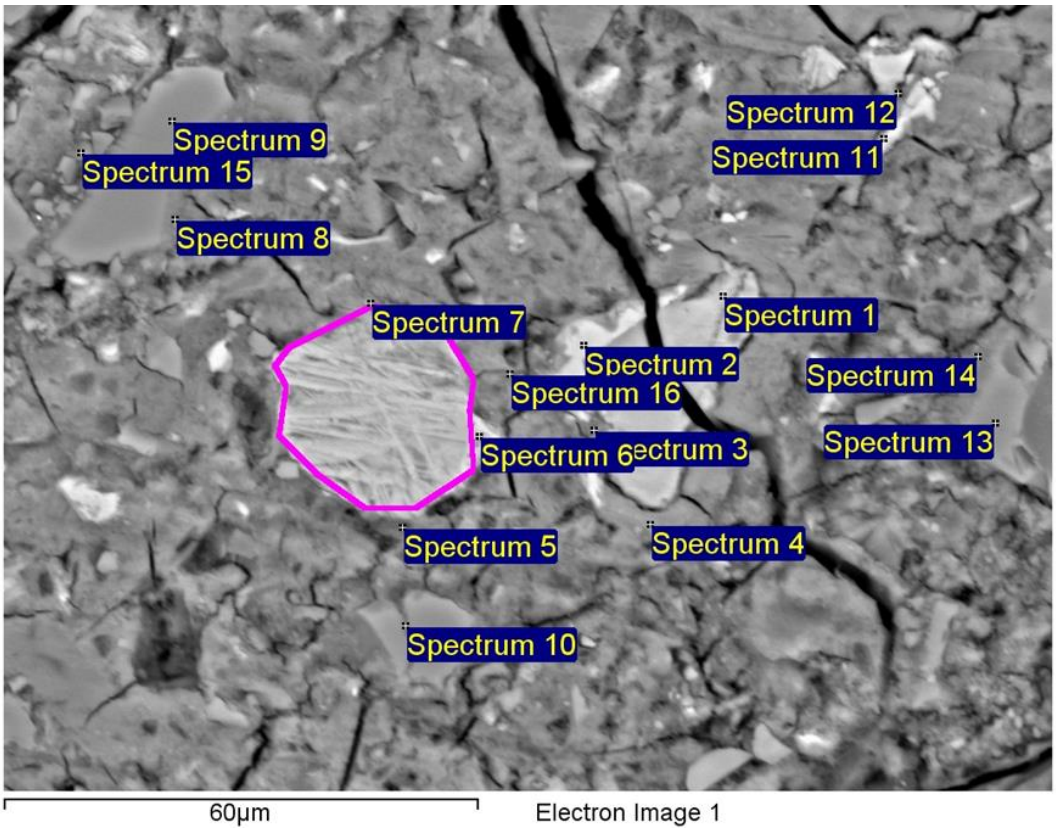

Figure 7.5. BSE of polished Q@20% section with selected locations for EDS.

Table 7.5. EDS values of selected locations from Figure 7.5.

	Composition (% by mass)										
Spectrum	SiO_2	CaO	Na_2O	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	TiO_2	P_2O_5	Mn_2O_3
1	29.01	68.22	-	0.81	0.66	1.09	-	0.20	-	-	-
2	5.71	50.57	-	20.58	19.97	2.64	-	-	0.53	-	-
3	29.04	59.64	0.73	4.73	1.80	2.22	0.87	0.96	-	-	-
4	41.02	51.14	0.57	2.93	0.97	2.39	-	0.99	-	-	-
5	19.51	72.86	0.38	1.59	1.20	0.46	2.27	1.74	-	-	-
6	9.62	53.42	-	23.01	9.71	2.18	1.76	0.30	-	-	-
7	32.24	60.06	0.40	2.62	2.01	0.79	1.35	0.53	-	-	-
8	57.71	25.39	1.10	9.97	0.44	3.36	-	1.17	0.85	-	-
9	62.25	21.58	0.59	11.86	0.44	2.64	-	-	0.63	-	-
10	59.99	24.50	0.59	10.66	0.42	2.86	-	0.33	0.65	-	-
11	13.87	42.38	0.95	18.56	19.60	2.90	0.49	0.80	0.44	-	-
12	22.16	58.73	0.88	5.27	10.54	1.33	-	1.10	-	-	-
13	62.37	21.13	0.74	11.80	0.43	2.94	-	0.00	0.59	-	-
14	59.51	23.62	1.31	9.77	0.56	3.12	-	1.44	0.67	-	-
15	76.95	17.13	-	2.95	0.46	0.81	0.85	0.66	0.19	-	-
16	30.86	58.25	0.61	3.28	1.31	0.83	4.14	0.72	-	-	-

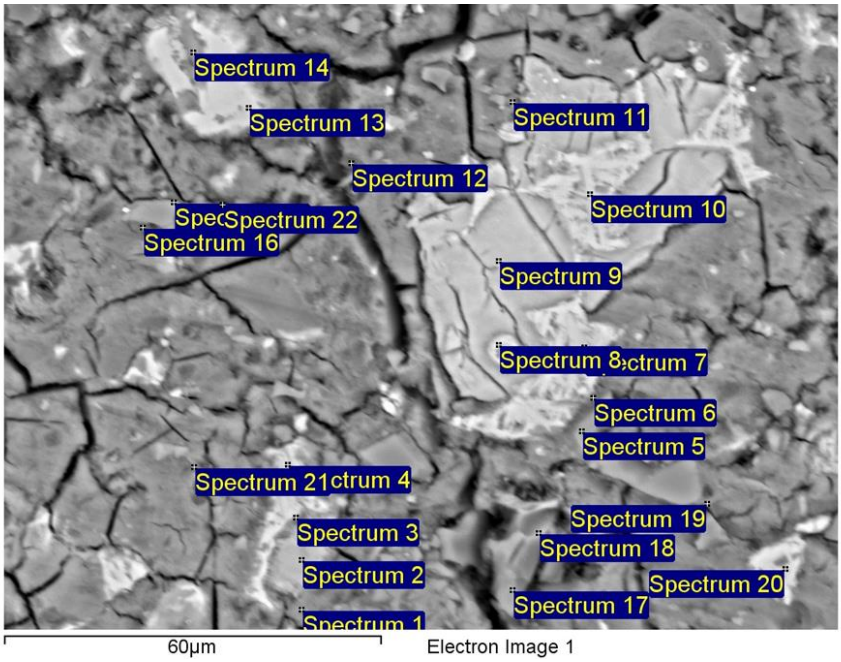

Figure 7.6. BSE of polished Q@20% section with selected locations for EDS.

Table 7.6. EDS values of selected locations from Figure 7.6.

	Composition (% by mass)										
Spectrum	SiO_2	CaO	Na_2O	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	TiO_2	P_2O_5	Mn_2O_3
1	37.23	46.83	2.40	3.65	1.23	2.04	2.40	3.90	0.32	-	-
2	35.41	63.13	-	-	0.56	0.38	-	0.52	-	-	-
3	16.89	62.02	0.51	5.92	11.18	1.08	0.57	1.38	0.45	-	-
4	5.78	48.25	-	20.99	20.55	3.57	-	0.26	0.60	-	-
5	61.22	22.04	0.73	11.79	0.54	2.89	-	0.23	0.56	-	-
6	40.59	43.54	0.35	7.16	3.20	2.06	1.37	1.00	0.73	-	-
7	4.76	50.96	-	23.07	17.71	2.82	-	0.23	0.46	-	-
8	16.89	51.48	-	18.33	9.85	2.70	-	0.36	0.39	-	-
9	26.40	71.37	-	0.85	0.60	0.78	-	-	-	-	-
10	5.11	50.15	-	21.92	19.40	2.62	-	0.22	0.58	-	-
11	35.35	51.00	2.19	3.72	2.17	2.12	-	3.19	0.25	-	-
12	26.79	54.04	1.05	7.24	2.35	1.12	3.74	3.68	-	-	-
13	4.51	49.11	-	20.40	22.72	2.55	-	-	0.70	-	-
14	13.62	51.14	-	16.95	14.34	2.03	1.92	-	-	-	-
15	56.10	24.79	1.65	10.47	0.52	3.67	0.85	1.39	0.57	-	-
16	33.72	53.86	0.65	4.28	1.66	1.04	2.87	1.92	0.00	-	-
17	63.05	19.64	0.93	12.44	0.33	3.07	-	-	0.53	-	-
18	62.72	18.91	1.38	12.48	0.36	3.34	-	0.33	0.50	-	-
19	46.12	38.65	2.71	4.15	0.67	1.29	0.92	5.48	-	-	-
20	7.46	48.56	-	21.45	17.12	3.87	1.20	-	0.34	-	-
21	24.93	55.81	0.74	9.42	2.28	0.99	4.43	1.39	-	-	-
22	23.90	64.85	0.77	3.07	2.51	0.65	2.71	1.54	-	-	-

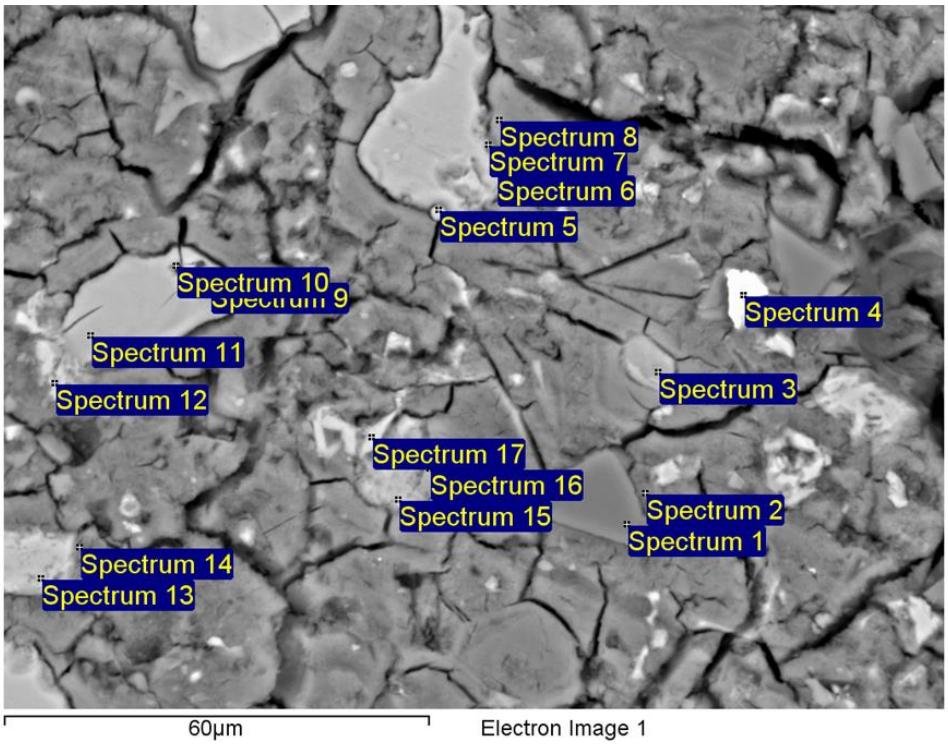

Figure 7.7. BSE of polished S@20% section with selected locations for EDS.

Table 7.7. EDS values of selected locations from Figure 7.7.

	Composition (% by mass)										
Spectrum	**SiO_2**	**CaO**	**Na_2O**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**SO_3**	**K_2O**	**TiO_2**	**P_2O_5**	**Mn_2O_3**
1	78.29	9.96	8.60	1.21	0.00	1.66	-	0.28	-	-	-
2	38.11	44.95	3.68	3.95	3.65	1.67	3.26	0.73	-	-	-
3	27.72	69.20	0.36	0.85	0.70	1.16	-	-	-	-	-
4	0.44	1.11	-	-	97.93	-	-	-	-	-	0.52
5	30.59	63.07	1.02	2.24	1.47	0.55	0.55	0.51	-	-	-
6	27.73	68.69	0.69	1.34	0.67	0.88	-	-	-	-	-
7	27.76	68.48	0.62	1.30	0.81	0.86	-	0.16	-	-	-
8	37.16	57.16	0.65	2.02	1.48	1.52	-	-	-	-	-
9	9.58	49.33	0.69	22.08	14.42	2.79	-	0.72	0.39	-	-
10	15.96	61.12	0.44	8.62	12.09	1.28	-	0.49	-	-	-
11	27.12	69.47	-	1.19	1.00	1.23	-	-	-	-	-
12	8.10	48.56	-	20.61	17.89	3.00	1.15	0.31	0.38	-	-
13	4.98	49.42	0.37	23.69	17.39	3.76	-	0.38	-	-	-
14	17.98	49.72	2.56	13.35	10.87	2.12	2.33	0.64	0.42	-	-
15	26.21	71.08	-	1.21	0.73	0.68	-	0.10	-	-	-
16	33.44	59.72	2.13	1.64	1.04	1.54	-	0.48	-	-	-
17	11.03	49.95	-	20.14	15.91	2.82	-	0.14	-	-	-

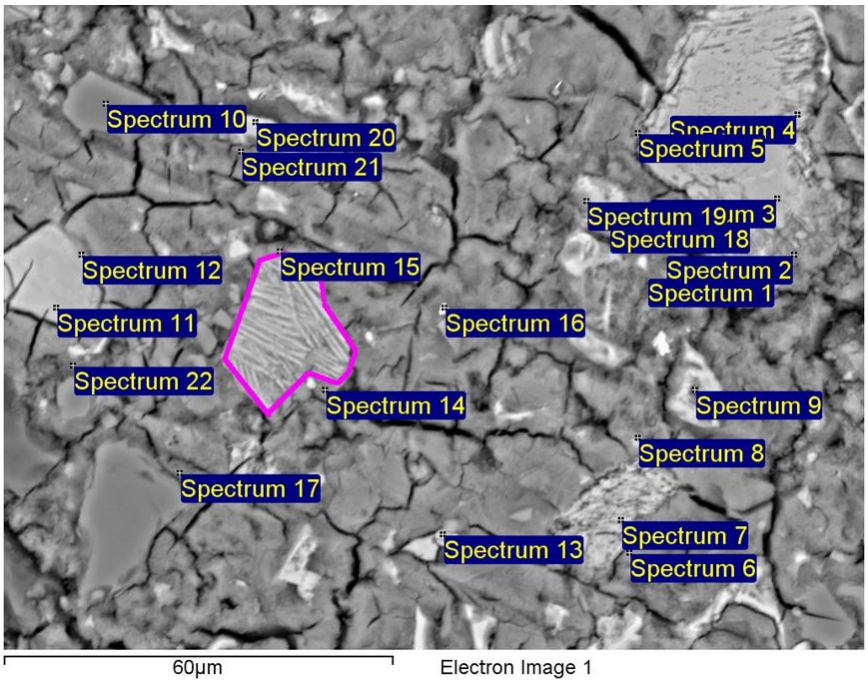

Figure 7.8. BSE of polished S@20% section with selected locations for EDS.

Table 7.8. EDS values of selected locations from Figure 7.8.

	Composition (% by mass)										
Spectrum	SiO_2	CaO	Na_2O	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	TiO_2	P_2O_5	Mn_2O_3
1	34.48	61.54	1.33	0.77	0.67	0.41	0.45	0.34	-	-	-
2	28.77	65.02	2.13	1.15	0.93	0.80	0.57	0.64	-	-	-
3	34.71	63.61	-	0.70	0.87	-	-	0.11	-	-	-
4	31.26	62.33	0.73	2.07	1.84	0.48	1.12	0.17	-	-	-
5	33.81	59.77	1.21	2.00	1.26	0.51	1.10	0.34	-	-	-
6	46.32	44.81	3.08	1.74	0.97	1.26	1.35	0.47	-	-	-
7	34.16	61.05	0.57	1.49	1.46	0.48	0.45	0.35	-	-	-
8	26.03	47.03	2.57	6.29	8.41	4.41	4.73	0.54	-	-	-
9	6.72	51.95	1.22	21.75	12.66	3.27	0.54	1.89	-	-	-
10	77.82	11.58	7.99	1.28	0.47	0.51	0.00	0.35	-	-	-
11	27.34	71.30	-	0.62	0.00	0.65	-	0.10	-	-	-
12	25.91	70.29	1.00	1.02	0.83	0.68	-	0.28	-	-	-
13	41.06	52.86	1.59	1.62	1.26	0.93	-	0.69	-	-	-
14	29.19	55.24	2.54	3.12	5.42	1.19	2.09	0.89	0.32	-	-
15	34.02	58.96	1.71	1.93	1.07	0.55	1.27	0.49	-	-	-
16	28.06	27.88	2.87	2.62	36.01	1.21	0.87	0.48	-	-	-
17	43.10	40.80	5.80	3.70	1.21	1.37	2.52	1.49	-	-	-
18	5.55	52.85	-	21.01	17.69	2.69	-	0.21	-	-	-
19	8.95	53.13	1.27	15.84	18.02	1.91	-	0.40	0.48	-	-
20	14.24	42.95	1.99	19.21	16.40	3.53	0.81	0.33	0.54	-	-
21	18.45	62.92	2.34	3.22	8.60	1.82	1.31	1.34	-	-	-
22	30.75	53.77	2.08	5.77	2.40	1.12	2.96	1.14	-	-	-

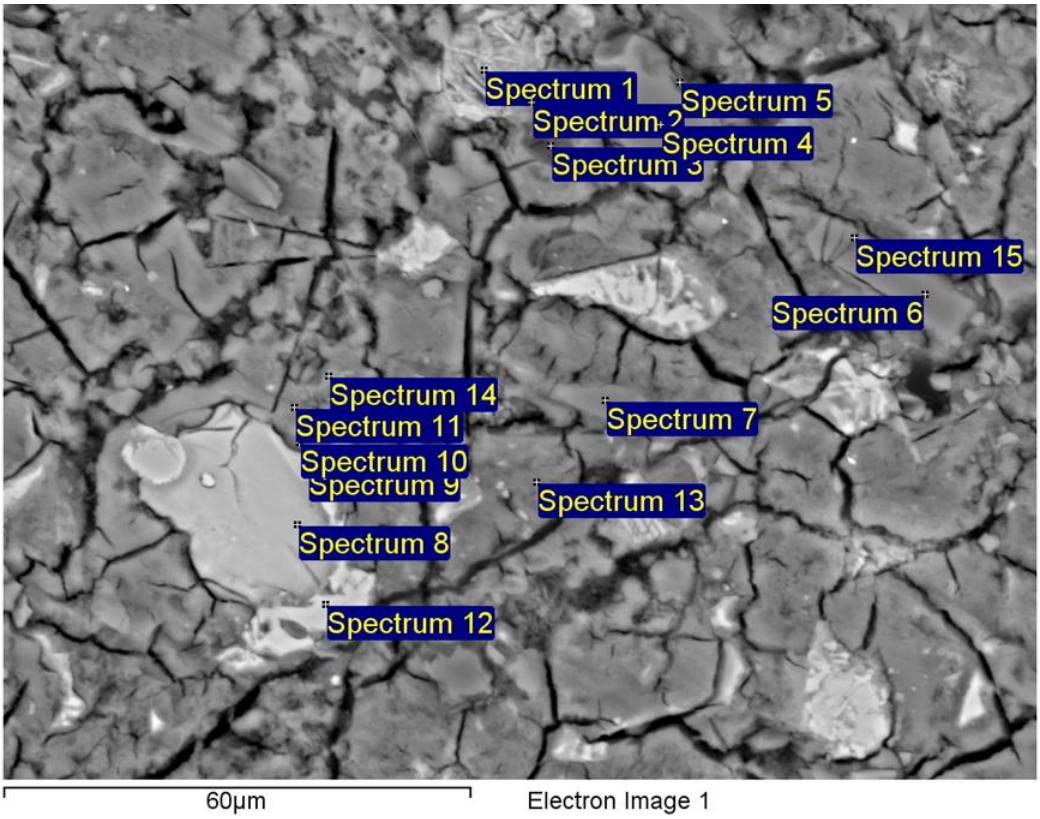

Figure 7.9. BSE of polished T@20% section with selected locations for EDS.

Table 7.9. EDS values of selected locations from Figure 7.9.

	Composition (% by mass)										
Spectrum	**SiO_2**	**CaO**	**Na_2O**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**SO_3**	**K_2O**	**TiO_2**	**P_2O_5**	**Mn_2O_3**
1	35.22	56.28	2.37	1.58	2.14	0.60	0.77	1.03	-	-	-
2	37.20	46.37	5.25	2.49	1.61	1.21	2.92	2.95	-	-	-
3	31.57	45.70	7.58	4.36	0.84	0.80	6.29	2.86	-	-	-
4	77.34	10.80	7.77	1.21	0.40	2.04	-	0.45	-	-	-
5	51.79	29.47	11.24	1.87	0.53	2.06	1.02	2.02	-	-	-
6	74.36	7.84	11.78	2.75	-	2.91	-	0.36	-	-	-
7	72.93	8.58	12.11	2.83	-	3.15	-	0.40	-	-	-
8	27.13	70.37	-	0.94	0.74	0.81	-	-	-	-	-
9	28.15	65.18	0.57	2.70	1.70	1.47	-	0.24	-	-	-
10	33.28	54.62	2.34	3.02	2.97	2.10	0.87	0.80	-	-	-
11	34.89	50.45	4.02	3.13	1.66	1.79	2.64	1.42	-	-	-
12	6.18	46.38	0.48	22.72	19.55	3.54	-	-	0.80	-	0.35
13	23.48	46.52	5.75	9.39	6.17	2.95	4.24	1.50	-	-	-
14	58.74	21.30	10.94	3.19	0.51	3.25	1.00	1.07	-	-	-
15	67.17	10.03	15.39	2.93	0.26	3.38	-	0.85	-	-	-

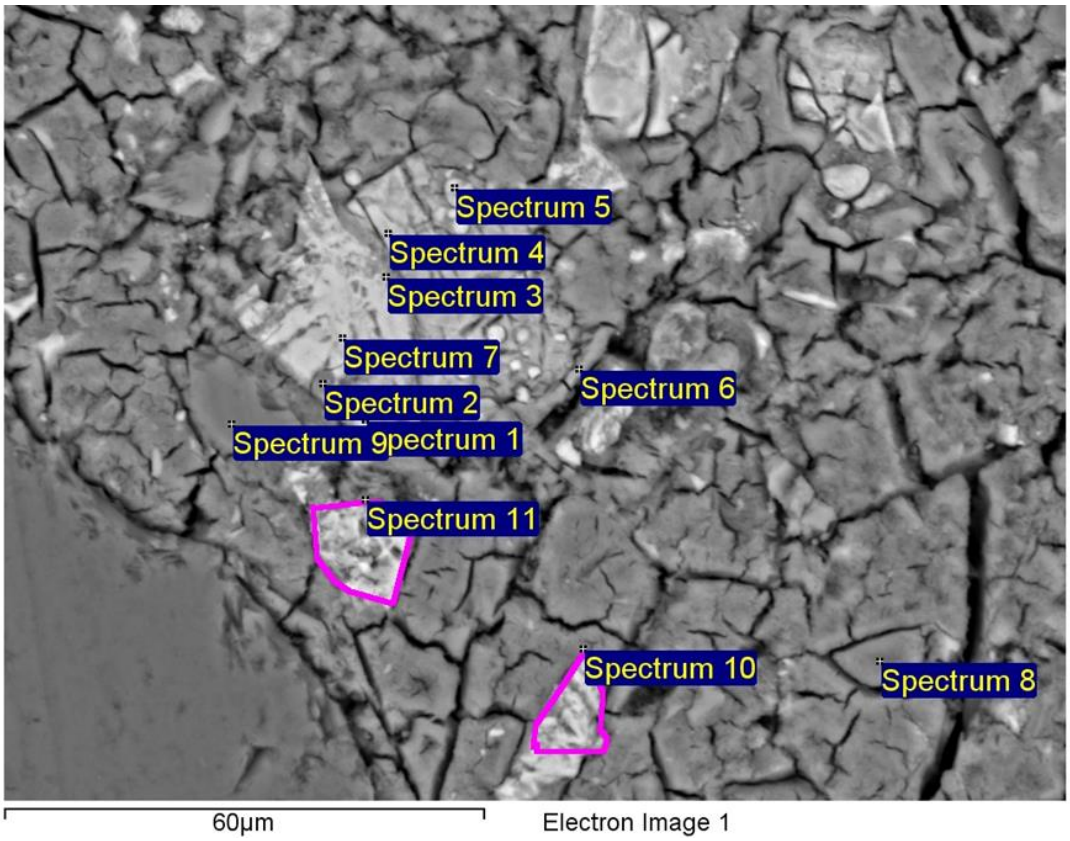

Figure 7.10. BSE of polished T@20% section with selected locations for EDS.

Table 7.10. EDS values of selected locations from Figure 7.10.

	Composition (% by mass)										
Spectrum	**SiO_2**	**CaO**	**Na_2O**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**SO_3**	**K_2O**	**TiO_2**	**P_2O_5**	**Mn_2O_3**
1	5.39	47.64	0.58	20.04	22.76	2.94	-	-	0.66	-	-
2	24.42	54.96	2.99	7.31	4.88	2.80	1.27	1.37	-	-	-
3	13.94	43.04	4.73	24.56	10.68	2.30	-	0.75	-	-	-
4	25.12	68.11	0.77	2.70	1.86	1.01	0.45	-	-	-	-
5	28.66	60.52	3.65	3.15	1.28	0.68	1.42	0.64	-	-	-
6	33.38	44.40	10.83	4.07	1.67	2.55	1.07	2.02	-	-	-
7	4.82	48.65	0.00	19.99	22.65	3.12	-	-	0.76	-	-
8	43.40	39.00	7.14	2.17	2.01	2.85	-	3.43	-	-	-
9	74.68	8.90	10.05	2.95	-	3.05	-	0.37	-	-	-
10	12.95	44.29	4.56	18.28	14.05	3.91	1.16	0.81	-	-	-
11	9.51	46.06	3.55	20.25	15.44	3.30	0.96	0.52	0.40	-	-